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Coastal and Hydraulics Laboratory

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National Shoreline Erosion Control Development and Demonstration Program

Chesapeake Bay Breakwater Database Project, Section 227 Demonstration Site: Hurricane Isabel Impacts to Four Breakwater Systems

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Final Report

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ABSTRACT: The use of breakwaters for shore protection on the Chesapeake Bay has increased over the past 15 years. A multiyear project evaluates post-construction data collected for 41 of these breakwaters and surrounding area including elevation surveys, vegetation, surveys, hydrodynamic analysis and photographs. This information is being accumulated into a database that will be available for evaluation and design reference and to aid in development of design guidance for short-fetch, shallow-water environments of the Chesapeake Bay and similar estuaries. In Fiscal Year 2003, six sites around the bay were chosen for detailed analysis. These surveys were conducted during the months of August and September. Shortly after these surveys were completed, Category 2 Hurricane Isabel hit the area on September 19, 2003. Post-hurricane surveys were immediately conducted at four of the six sites, and the data sets were included in the database. Analysis of these data sets indicates the breakwaters provided significant protection to the land in the lee of the breakwaters and that the structures experienced little or no damage. Additionally, the sand introduced into the sediment budget as a result of the storm cutting into the banks of adjacent unprotected properties may have enhanced the breakwater systems by accelerating the equilibrium beach-building process. This report presents the results of the pre- and post-hurricane breakwater evaluation.

Contents

Preface

Virginia Institute of Marine Science (VIMS) is conducting this study under the direction of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Coastal Engineering Branch, the U.S. Army Engineer District, Baltimore, and the U.S. Army Engineer District, Norfolk, Coastal Planning and Coastal Engineering Branches. Funding was provided by the National Shoreline Erosion Control Development and Demonstration Program (Section 227). The program was authorized by the Water Resources and Development Act of 1996 (Public Law 104-303, 110 Statute 3658), dated 12 October 1996. Mr. William R. Curtis, CHL, is the Section 227 Program Manager. Ms. Cheryl Pollock, CHL, is the Chesapeake Bay Breakwaters work unit Principal Investigator. Mr. Mark Hudgins, Norfolk District, and Ms. Karen Nook, Baltimore District, are the project managers.

Work was performed under the general supervision of Dr. Yen-Hsi Chu, former Chief, Coastal Engineering Branch, CHL; Ms. Joan Pope, previous Principal Investigator and former Technical Director for Flood and Coastal Storm Damage Reduction, CHL; Dr. Jack Davis, Technical Director for Flood and Coastal Storm Damage Reduction, CHL; Mr. Thomas W. Richardson, Director CHL, and Dr. William D. Martin, Deputy Director, CHL. This report was prepared by VIMS under the direction of Mr. Scott Hardaway, Jr., and a technical review was conducted by Ms. Pollock and Mr. Curtis. Ms. J. Holley Messing, CEB, completed final formatting of the report.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC and COL James R. Rowan, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Hurricane Isabel made a substantial impact on Chesapeake Bay on 18 September 2003 with record high storm surge and winds. Virtually all Chesapeake Bay shorelines were impacted. Those shorelines with open fetch exposures to the north, northeast, east, southeast, and south were especially affected due to the rotation of Isabel's winds from north to south during her passage. Hundreds, if not thousands, of shore protection systems were damaged or destroyed. Many shorelines around the bay, which had no shore protection, were moved 3.0 to 9.1 m (10 to 30 ft)[1] landward due to storm surge and waves. Shore reaches with properly designed and constructed headland breakwater systems incurred varying degrees of damage from none to several feet of cut at the base of the adjacent upland banks. This report documents the impact of Hurricane Isabel on four such systems in Chesapeake Bay. These sites are part of the Chesapeake Bay Breakwater Database.

The Chesapeake Bay Breakwater Database is being developed by personnel in the Virginia Institute of Marine Science's (VIMS) Shoreline Studies Program for the U.S. Army Corps of Engineers (USACE) in order to:

a. Document breakwater system performance around Chesapeake Bay relative to predictions.

b. Develop guidelines for breakwaters in sand-limited and fetch-limited systems such as estuaries, reservoirs, lakes and bays.

This project is part of the National Shoreline Erosion Control Development and Demonstration Program (Section 227). The program's objective is to provide state-of-the-art coastal shoreline protection with emphasis on evaluation of innovative or nontraditional approaches to help prevent coastal erosion and to improve shoreline sediment retention.

The Chesapeake Bay Breakwater Database Project has 42 sites along the Chesapeake Bay in Virginia and Maryland (Figure 1). Although more bay breakwater systems exist, the sites in the database were chosen because they were designed with regard to their site setting, impinging wave climate, and desired level of protection, i.e., the 25-year or 50-year storm event. Many projects are older than 10 years, and all were affected by Hurricane Isabel. Aquia Landing, Kingsmill, Van Dyke, and Yorktown, VA, were selected for detailed analysis of Isabel's impacts since the four sites were surveyed immediately prior

[1] Units of measurement in the text of this report are in SI units followed by non-SI units in parenthesis. In addition, a table of factors for converting non-SI units of measurement used in figures in this report is presented on page vi.

to the storm. This provided an opportunity to physically determine shore changes that may result due to a major storm event that equaled the 1933 hurricane in storm surge level. The hurricane of 1933 is the unofficial 100-year event that the Federal Emergency Management Agency (FEMA) has, until this point, used for a reference datum in Chesapeake Bay.

These four sites were mapped using a real-time kinematic global positioning system before and after the storm. The data were analyzed for changes in sand levels in the beach and nearshore as well as for any upland or backshore impacts from the storm. To better understand these changes, low-level vertical aerial photography, taken before and after the storm, were geo-rectified and the shorelines digitized. At all sites, the breakwaters performed well allowing little overall change to beach systems. Since these sites were designed for 25- and 50-year storms, all were overtopped with the combination of surge and wave runup. The beach/upland interface at the two high bank sites (Kingsmill and Van Dyke) incurred varying degrees of bank scarping, but no bank failure while at the two low backshore sites (Aquia Landing and Yorktown), sand washed over into adjacent roadways. Beach planforms adjusted bayward under storm conditions but returned to pre-storm position.

2 Shore Management

When developing a framework for shoreline management, establishing clear objectives is necessary. In developing management plans, the following objectives should be given consideration:

a. Prevention of loss of land and protection of upland improvements.

b. Protection, maintenance, enhancement and/or creation of wetlands habitat both vegetated and nonvegetated.

c. Management of upland runoff and groundwater flow through the maintenance of vegetated wetland fringes.

d. Address potential secondary impacts for a selected strategy within the reach, which may include impacts to downdrift shores through a reduction in the sand supply or the encroachment of structures onto subaqueous land and wetlands.

e. Provide access and/or creation of recreational opportunities such as beach areas.

These objectives must be assessed in the context of a shoreline reach. While all objectives should be considered, each one will not carry equal weight. In fact, satisfaction of all objectives for any given reach is not likely as some may be mutually exclusive. For instance, the type of shore (i.e., marsh, beach, bank) and ownership of downdrift property may alter management strategies as potential impacts are discussed in the design process.

Sites with a natural or environmental edge provide protection from coastal hazards such as storms. Wider beaches allow the waves to dissipate before striking the backshore. Vegetation serves to stabilize the substrate during storm events. Low marshes may be completely overwashed by surge and mitigate the impact of waves while maintaining their structure since marsh is naturally more resistant to erosion than unconsolidated (i.e., sand) substrate. Dunes provide a natural backstop to waves before they impact the upland. In fact, Milligan et al. (2005b) found that natural dunes at nine sites within the Chesapeake Bay estuarine system are naturally resilient and recover quickly. They protected upland structures from direct wave attack and mitigated any impact to upland banks. In developing management strategies, incorporating these features into shore protection in a cost-effective manner enhances the overall system.

Modeling Coastal Structures in Chesapeake Bay

Shore management utilizes wind/wave modeling in order to assess wave climate on a reach basis. The computer models SMB and RCPWAVE are used. SMB (Kiley 1980) generates a predicted wave height and period based on the effective fetch and offshore bathymetry of a site. RCPWAVE is a linear wave propagation model designed for engineering applications. This model, originally developed by the USACE (Ebersole et al. 1986), computes changes in wave characteristics that result naturally from refraction, shoaling, and diffraction over complex shoreface topography. To this fundamentally linear-theory-based model, routines have been added which employ wave bottom boundary layer theory to estimate wave energy dissipation due to bottom friction (Wright et al. 1987). Over the years, a three-step process has been developed (Hardaway et al. 1995; Hardaway and Gunn 1999a; Hardaway and Gunn 1999b) to: (a) assess the wind/wave climate using model SMB, (b) calculate the nearshore/nearfield wave refraction using RCPWAVE (Ebersole et al. 1986), and (c) plot pocket beach shore planforms using model SEB (Hsu et al. 1989).

Utilizing the output from the RCPWAVE model as input to the Static Equilibrium Bay (SEB) model, the equilibrium planforms between structures can be determined. Beach planform calculations use the annual significant wind-generated wave approach direction and selected design storm conditions such as the 25- and 50-year events. This procedure was first developed by Silvester (1970) and later refined by Hsu et al. (1989) and Silvester and Hsu (1993). Their methods were developed along open-ocean, coastal embayments usually influenced by a unidirectional, significant annual wave field. In Chesapeake Bay, there often is a bimodal annual wind field that generates a bimodal wave climate that must be accounted for in beach planform design. This sometimes results in embayments with two tangential beach sections at any one time as beach planforms from one wind-generated wave field replaces or resides with another. The equation is simply a way to calculate the general shape of the bay. Once you have the control line length (R_o) and angle from the wave crest line (β), you can determine the length of R for various wave angles (θ) (Figure 2). Figure 3 shows the relationship of the three parameters in beach planform design that can be used for predicting bay shape.

The relationship between four specific headland breakwater system parameters were investigated by Hardaway et al. (1991) and Hardaway and Gunn (1991) for 35 breakwater embayments around Chesapeake Bay. Referring to Figure 3, these parameters include breakwater crest length, (L_B), gap between breakwaters (G_B), backshore beach width (B_m) and embayment indentation (M_b). The midbay backshore beach width and backshore elevation are important design parameters because they determine the size of the minimum protective beach zone in the headland breakwater system. This beach dimension often drives the bayward encroachment that is required for a particular shore protection design. Linear regression analyses were best for the relationship of M_b vs. G_B with a correlation coefficient of 0.892. The ratio of these two parameters is about 1:1.65 and can be used as a general guide in siting the breakwater system for preliminary analysis. Then, the detailed bay shape using the SEB can be obtained. Stable relationships for M_b and G_B are not valid for transitional bay/breakwater segments that interface the main headland breakwater system

with adjacent shores. Numerous variations can occur depending on design goals and impinging wave climate.

Hardaway and Gunn (2000) found that for 14 breakwater sites around the Bay, the M_b vs. G_B ratio varies in range and average for bimodal and unidirectional wind/wave settings. For unidirectional sites, the range of M_b:G_B can be 1:1.4 to 1:2.5 with an average of 1:1.8. Aquia Landing and Yorktown have average M_b:G_B of 1:2.5 and 1:1.8, respectively. For bimodal sites M_b:G_B ratios vary from 1:1.0 to 1:1.7 with an average of 1:1.6. Kingsmill and Van Dyke have M_b:G_B ratios of 1:1.2 and 1:1.7, respectively.

Coastal Structures for Shore Management

Revetments are shoreline-armoring systems that protect the base of eroding upland banks and usually are built across a graded slope (Figure 4). The dimensions of the revetment depend on bank conditions and design parameters such as storm surge and wave height. These parameters also determine the size of the rock required for long-term structural stability. Generally, two layers of armor stone are laid over a bedding stone layer with filter cloth between the earth subgrade and bedding layer.

Stone breakwaters and sills are freestanding structures designed to reduce wave action by attenuation, refraction, and diffraction before it reaches the upland region. A sill (Figure 5) has a lower crest, is closer to shore, and usually, is more continuous than larger breakwater units. Sills can be used in combination with larger breakwater units. Sills are installed with beach fill to create a profile for establishing a marsh fringe.

Attached or headland breakwaters require beach fill in order to acquire long-term shoreline erosion control (Figure 6) since they are constructed in areas that are subject to more energetic conditions. Headland breakwaters can be used to accentuate existing shore features. The dimensions of a breakwater system depend on the desired degree of protection and potential impacts on littoral processes. Spurs are similar to breakwaters and sills in that they are freestanding structures. The distinction is that spurs are attached to the shoreline or another structure; the unattached end of the spur acts as a breakwater by diffracting incoming waves.

3 Site Information

Aquia Landing

Aquia Landing is a county-owned public beach on the Potomac River in Stafford County, VA (Figure 7). Prior to the project installation, the county beach was severely deteriorated with failing groins and washovers across a low upland shore zone (Figure 8a). Long fetch exposures to the southeast of over 7 nautical miles (n.m.) and northeast of over 4 n.m. made the site vulnerable to storm damage. Dominant northwest wind-driven waves and northeasters create a generally unidirectional wave exposure coming down the Potomac River. With partial funding from the Virginia Board on Conservation and Development of Public Beaches, a breakwater and beach-fill project was installed in 1987. The project covered 365.8 m (1,200 ft) of shoreline and consisted of 213.4 m (700 ft) of stone revetment, four 33.5-m (110-ft) headland breakwaters with 15,291.1 cu m (20,000 cu yd) of beach fill bounded on each end by spurs (Figure 8b). Downdrift impacts were considered negligible due to low marsh composition and property ownership being the same as the breakwater system. The design utilized the shore morphology of the existing groin field to determine tangential beach orientation. The SEB model was then applied to assess the predicted beach planforms for the headland breakwater systems (Hardaway et al. 1993; Hardaway et al. 1995; Hardaway and Gunn 1999a; Hardaway and Gunn 1999b; and Hardaway and Gunn 2000). The pocket beach configurations have been stable since installation. The overall purpose of the project was to provide shore protection, create a recreational beach, and reduce beach hazards from deteriorating groins.

The design and performance of the site was analyzed by Linden et al. (1991). They found that during the 3 years after the installation of the project, the overall volume of beach material within the monitoring area had not changed. The wide, flat, shallow nearshore has allowed submerged aquatic vegetation (SAV) to expand at the site in the last 10 years (VIMS 2005). This has likely helped maintain a stable nearshore during storm events.

Kingsmill

Kingsmill is located on the north shore of the James River in James City County, VA (Figure 7). It is a privately owned site that had chronic bank erosion and which has a long fetch exposure to the south of over 19.3 km (12 miles) and the southwest of over 8.0 km (5 miles). Wind frequencies from these directions are about the same, and the site occurs in what is considered a bimodal

wind/wave setting. The developer of the upscale residential community wanted shore erosion control with environmental edge (Figure 9a). A 853.4-m (2,800-ft) breakwater system was installed in 1996. It consisted of six headland breakwaters ranging in size from 35.1 m (115 ft) to 64.0 m (210 ft), a 33.5-m- (110-ft-) low breakwater and a 51.8-m (170-ft) revetment for boundary interfacing structures, beach fill, and wetlands plantings, all of which were designed for a 50-year storm event (Figure 9b). The site's 21.3-m- (70-ft-) high banks had little sand and posed potential upland drainage problems. The design routed upland drainage to an adjacent marsh, and low swales in the bank were used to allow storm water to diffuse through a vegetated beach fill. Beach fill was obtained from an upland borrow pit. The design utilized existing reach morphology and shore erosion patterns along with a hydrodynamic analysis, which included SMB, RCPWAVE, and SEB models for a bimodal wave climate. The overall purpose of the project was to provide shore protection and habitat enhancement.

Van Dyke

Van Dyke is located on the south shore of the James River in Isle of Wight County, VA (Figure 7). It is a privately owned site that had severe erosion of its 15.2-m (50-ft) banks due, in part, to its exposure to a long fetch to the north of over 19.3 km (12 miles) (Figure 10a). The site is affected by wind/waves from the northwest, north, and northeast and is defined as a bimodal site. The site's bimodal wave climate and sand rich banks called for a breakwater system, which utilized the bank sand for beach fill. Several factors were important considerations in the design; these were impacts to adjacent properties and the coordination of 15 property owners with varying degrees of support for and input to the project. However, the 701-m (2,300-ft) project was installed in 1997. The system consisted of eight headland breakwaters ranging in size from 27.4 m (90 ft) to 48.8 m (160 ft) with open upriver boundary and a low short 15.2-m (50-ft) interfacing breakwater and revetment downriver (Figure 10b). The project also included beach fill and wetlands plantings. Beach-fill sand was selectively mined from adjacent 12.2-m (40-ft) upland banks when they were graded. The overall purposes of the project were to provide shore protection and access to the James River.

Yorktown Public Beach

The Yorktown Public Beach is located on the south side of the York River in Yorktown, VA (Figure 7). It is approximately 365.8 m (1,200 ft) in length. Historically, the beach was a product of erosion of nearby sandy upland banks and the littoral transport system. Over the years, the beaches along the waterfront began to narrow as the natural sediment supply was depleted by hardening of the updrift shorelines. Beaches were easily overwashed in storms, and they continued to erode (Figure 11a). The nearshore closest to the Colman Memorial Bridge deepens as the river narrows. The channel under the bridge is naturally 27.4 m (90 ft) deep. Downriver, the nearshore widens toward the National Park Service property. Although the winter northwesters are strong, the

long fetch to the east into the bay and the shoreline morphology indicate a unidirectional wind/wave setting.

In 1978, York County installed a riprap revetment along its picnic area shore to the east end of Yorktown. This area had been filled in Colonial days to expand the warehousing facilities at the Port of Yorktown. After a damaging storm in November 1985, a small breakwater with beach nourishment was installed in order to maintain a storm water outfall (Figure 11b). Subsequent renourishment occurred 3 years later.

In September 1994, York County installed Phase I of an offshore breakwater system, which consisted of two shore-attached breakwaters (Figure 11c). These breakwaters, 36.6 m (120 ft) and 42.3 m (140 ft) in length, were coupled with 5,734.2 cu m (7,500 cu yd) of beach fill and plantings of *Spartina alterniflora* and *S. patens* in the lee of the structure. The preexisting breakwater was modified to interface the system on the downstream end and the 36.6-m (120-ft) breakwater has a falling crest elevation to encourage wave refraction, and a winged breakwater was designed to achieve a reasonable interface with the adjacent shore and reduce potential wave force impacts during northeasters. In May 1996, approximately 458.7 cu m (600 cu yd) of sand was dredged from under the Coleman Bridge as part of the bridge widening project. This sand was subsequently used as beach fill on Yorktown Beach.

In the fall/winter of 1998-1999, Phase II of the Shore Erosion Control Plan was implemented along the shoreline (Figure 11c). Two winged, headland breakwaters, 36.6 (120) and 39.6 m (130 ft) in length, were constructed downriver from the existing breakwaters. The small breakwater built in 1986 to stabilize the storm water outfall was removed in order to establish a better breakwater gap-to-bay indentation ratio for the new system. The storm water outfall pipe was relocated through one of the new breakwaters. In addition, approximately 7,645.5 cu m (10,000 cu yd) of sand was placed on the beach, and beach grasses were planted behind the structures.

Phase III of breakwater construction began in June 2000. The completed project included three new breakwaters, beach fill along the Yorktown waterfront, and a revetment. Since then, the wharf where the old post office sat was removed. Two smaller breakwaters, 24.3 (80) and 25.9 m (85 ft) in length were positioned at the far west of the reach. A larger winged, headland breakwater, 45.7 m (150 ft) in crest length, was installed as well, and beach grasses were planted behind it. The existing revetment on the upriver end of the site was repaired and a new section was added toward the west. Along with the breakwater construction, a new walkway adjacent to the Water Street was added (Figure 11c).

Since then, two additional breakwaters have been built on the upriver end of the site, and in 2005, three more were constructed upriver and one more downriver. History of the site, design guidelines, and performance of the Yorktown site over time has been documented in Milligan et al. (1996) and Milligan et al. (2005a).

4 Hurricane Isabel

Hurricane Isabel made landfall along the southeast coast of North Carolina on 18 September 2003. At one time, the storm was a Category 5 on the Safir-Simpson scale. It had been downgraded to a Category 2 before it made landfall (Figure 12). By the time it hit Chesapeake Bay, it was a minimal Category 1. However, in addition to being in the right-front quadrant of the advancing hurricane, southeastern Virginia experienced east and east-southeast winds, which are known to have the greatest potential to transport water into Chesapeake Bay and its Virginia tributaries. The hurricane's impact reached as far inland as Lake Erie.

The extent of coastal flooding during a storm depends largely on both the background astronomical tide and the surge generated by the storm's high winds and low atmospheric pressure. Together, surge and astronomical tide combine to form a storm tide. Storm-tide flooding is maximized when the storm surge and a rising tide reach their peak at the same time. The National Oceanic and Atmospheric Administration's (NOAA) SLOSH model (Figure 13) depicts the maximum predicted surge levels around the bay. However, it may have underpredicted certain areas, particularly up the rivers (http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml). Measured storm impacts would seem to indicate higher surges than the model predicted.

The hurricane of 1933, widely known as the "storm of the century" for Chesapeake Bay, generated a storm surge in Hampton Roads of 1.8 m (5.84 ft), more than a foot higher than the 1.45-m (4.76-ft) storm surge recorded for Hurricane Isabel. Yet many long-time Tidewater, VA, residents say that the high-water marks left by Isabel equaled or exceeded those of the 1933 storm (Boon 2003).

An analysis of sea-level records shows that Isabel's coastal flooding matched that of the August 1933 storm due to the long-term increase in sea level in Hampton Roads (Boon 2003). Data from a tide monitoring station at Sewells Point show that sea level in Tidewater, VA, rose 0.41 m (1.35 ft) between August 1933 and September 2003. Based on storm surge and astronomical tide, the 1933 hurricane storm surge exceeded Isabel's by more than a foot. Its surge also occurred at the beginning of spring tides while Isabel's surge occurred in the middle of a neap tide. However, the increase in sea level at Hampton Roads in the 70 years between the two storms was enough to boost Isabel's storm tide to within 3.8 cm (an inch and a half) of the level experienced during the 1933 storm (Boon 2003).

Additional storm data were obtained by an Acoustic Doppler Current Profiler (ADCP), which was deployed in 8.5 m (28 ft) of water offshore of VIMS at Gloucester Point. The instrument provided a quantitative record of the hurricane's impact on lower Chesapeake Bay. Data from the ADCP showed that Isabel created a 2.1-m (7-ft) storm tide topped by 1.8-m (6-ft) waves. At the height of the storm, wave crests were passing over the instrument once every 5 sec, and the storm was forcing the entire flow of the York River upstream at a rate of 2 knots. Because Isabel was so large, its winds, waves, and surge affected the bay for an abnormally long time. The ADCP data showed that storm conditions persisted in the bay for nearly 12 hr and that wave-driven currents were strong enough to mobilize bottom sediments even at the instrument's depth, increasing water turbidity by a factor of two to three compared to fair-weather conditions (VIMS 2003).

Weather data provided by instruments atop VIMS' Byrd Hall showed that maximum sustained winds on the campus reached 104.6 km/hr (65 mph), with 144.8-km/hr (90-mph) gusts. The barometer bottomed out at 74.2 cm (29.2 in.), with a rainfall accumulation of about 5.6 cm (2.2 in.) (VIMS 2003).

Around the bay, similar impacts were recorded by tide gauges (Figure 14). The location and records of five tide gauges indicate the widespread flooding that occurred due to the storm. In the lower bay, the Sewells Point and Chesapeake Bay Bridge Tunnel gauges survived the storm and indicated a total water level of el[1] 8 and el 7.5 above mean lower low water (mllw) at the peak of the storm. This is about 1.5 m (5 ft) above normal. Also of note, the tide was running higher than normal for the day before the storm and the 2 days after at both locations. In fact, on the day after the storm at Sewells Point, the lowest tide was higher than the predicted high tide of el 2.5.

The other three tide gauges were destroyed during the storm before the peak water level was reached (Figure 14). At Gloucester Point on the York River, the tide gauge stopped recording at el 8.5 during the storm. Maximum measured still-water level across the river at Yorktown was el 8.6 with the trash line indicating the water plus waves was at el 12.5. That is a surge above the mean range 0.73 m (2.4 ft) of 1.8 m (6 ft) with additional 1.2 m (4 ft) waves. Kingsmill, on the James River, stopped recording at el 6.5. At this location, measured trash lines indicated that the maximum surge and wave level was about el 12 or about 2.4 m (8 ft) above the mean tide range.

The NOAA analyzed tide gauge data from all over Chesapeake Bay. The report states that storm surge was generally lower and more variable in the lower Chesapeake Bay than those in the upper Chesapeake Bay. Also, surges at the open bay sites were lower than those located in the more restricted rivers (Hovis et al. 2004). Their data show that the Hurricane Isabel tide levels exceeded the historical maximum water levels at two sites in the lower bay whose gauges were still in operation after the storm. These gauges were located at Lewisetta on the Potomac River and at the Chesapeake Bay Bridge Tunnel. The previous storm of record at these two sites was the Twin Northeasters in January/February 1998. The upper bay also was severely impacted by the storm. Tide gauges in Maryland at Cambridge, Annapolis, Tolchester, Baltimore, and Chesapeake City

[1] All elevations (el) cited herein are in feet referenced to mean lower low water (mllw). To convert feet to meters, multiply number of feet by 0.3048.

all exceeded the historical maximum water levels during Hurricane Isabel. These stations are generally located at the headwaters of large rivers or bays where the storm's persistent winds pushed water into enclosed areas and held it there through a complete tidal cycle (Hovis et al. 2004). At many sites, particularly in the upper Bay and rivers, the peak of the storm surge lagged behind high tide. At Sewells Point on the James River, the peak storm surge occurred about 2 hr after predicted high tide while at Lewisetta on the lower Potomac River, the peak occurred about 3.5 hr after predicted high tide. The lag was even greater up the rivers and bay, some even as much as 8 hr after predicted high tide. In fact, the maximum observed water level and peak storm surge in the upper Chesapeake Bay did not occur until the storm center had already reached Lake Erie (Hovis et al. 2004).

5 Methods

Site Surveying

A shoreline and nearshore survey was performed at each breakwater site during the summer of 2003 serving as the pre-hurricane survey. After the passage of the storm, a post-storm survey was performed at each site. A Trimble 4700 Real-Time Kinematic Global Positioning System (RTK-GPS) was used to set site control and acquire shore data. The 4700 receiver utilizes dual-frequency, real-time technology to obtain centimeter accuracy in surveying applications. In addition, a Trimble 5600 Robotic Total Station was used to acquire data in the nearshore.

Base station benchmarks were preset at each site with a 2-hr occupation. These data were processed through the National Geodetic Survey's On-line Positioning User Service (OPUS) (http://www.ngs.noaa.gov/OPUS/). All the survey data were based on these benchmarks. In addition, 3-min occupations were taken at secondary benchmarks in order to determine survey error. After the hurricane, many benchmarks needed to be reset. The horizontal datum is UTM, Zone 18 north, NAD83, international feet. The vertical datum is feet mllw, geoid99, as determined from nearby benchmarks publishing both NAVD88 and mllw for the 1960-1978 tidal epoch (http://www.co-ops.nos.noaa.gov/bench_mark.shtml?region=va).

Generally, the surveys included the following elements:

a. Dimensions of the project structures.

b. Mean high water (mhw) and mean lower low water (mllw); survey extends to approximately the -3 ft mllw contour.

c. Base of bank, mid-bank and top of bank, where appropriate and possible.

Survey dates and site length are as follows:

Aquia Landing	12 August 2003	30 September 2003	335.3 m (1,100 ft)
Kingsmill	21 August 2003	6 October 2003	701 m (2,300 ft)
Van Dyke	20 August 2003	21 October 2003	670.6 m (2,200 ft)
Yorktown	June 2003	25 September 2003	548.6 m (1,800 ft)

Storm Photographs, Georeferencing, and Mosaicking

Recent color aerial photography was acquired by Shoreline Studies Program to help estimate, observe, and analyze shoreline changes before and after Hurricane Isabel impacts on the breakwater sites on 18 September 2003. The images were scanned as Tagged Image File Format (tiff) files at 600 dots per inch (dpi). ESRI ArcMap GIS (www.esri.com) software was used to georeference the images for Van Dyke, Aquia Landing, Kingsmill, and Yorktown. The reference mosaic, the 2002 Digital Orthophotos from the Virginia Base Mapping Program (VBMP), is divided into a series of orthophoto tiles and is stored in a Virginia south, state plane projection, in feet. The aerial photo tiles from VBMP for each site were mosaicked and reprojected to a UTM zone 18 north, NAD83 projection, in meters.

Rectifying requires the use of ground control points to register the aerial photography to the reference images. Ground control points are points that mark features found in common on both the reference images and on the aerial photographs that are being georeferenced. Control points were distributed evenly to maintain an accurate registration without excessive amounts of warp and twist in the images. In addition, where possible, enough control points were placed within the area of interest, the shoreline and the breakwaters, to ensure accurate registration in these key areas. This can be challenging in areas with little development. Good examples of control points are permanent features such as man-made objects and stable natural landmarks. The standard in this project was to achieve a root mean square (RMS) error under six for each aerial photograph.

Georeferencing was done by using the Georeferencing Tool in ArcMap. First the reference image and the scanned aerial photograph are roughly aligned so that common points can be identified. Then, with the aid of the Georeferencing Tool, ground control points are added until the overall RMS error is less than six and the location of the aerial photograph closely matches the location of the reference image. When an acceptable correspondence is achieved, the aerial photograph is saved as a rectified image. All the rectified images were then mosaicked using the mosaic tool in ERDAS Imagine (http://www.gis.leica-geosystems.com/Products/Imagine/).

6 Results

Aquia

Isabel hydrodynamic

Aquia Landing's east-facing shoreline has a nearly north-south orientation. Winds from the north, northeast, east, southeast, and southerly directions will impact this beach. Storm surge measurements at Colonial Beach (Figure 14) stopped at about 6 p.m. on 18 September 2003 when the pier to which the gauge was attached was destroyed. The tidal elevation had reached about el +5.5 and was still climbing. Normal high tide at Colonial Beach is about 4 hr ahead of Aquia Creek. Mean tide range is 0.5 m (1.6 ft) in Colonial Beach and 0.4 m (1.3 ft) at Aquia Landing. The closest operating wind gauge during Isabel was at Lewisetta some 61.2 km (38 miles) southeast down the Potomac River. On the day of the storm, northeasterly winds were increasing and sustained at 41.8 km/hr (26 mph) at about noon. By 4 p.m., they had reached 69.2 km/hr (43 mph) and were arriving from the east-northeast. At this time, a storm surge of about el +2.2 may have been impacting Aquia's shoreline. As the wind increased, its direction slowly shifted to the east then southeast resulting in a window of significant wind/wave impacts occurring between 6 p.m. and 10 p.m. as the surge rose. The peak sustained winds (85.3 km/hr (53 mph) from the east-southeast) occurred about 8 p.m. on 18 September. However, interpolated peak surge at Aquia was about 10 p.m. when sustained wind speeds had dropped to 69.2 km/hr (43 mph) from the southeast at Lewisetta. Maximum still-water level at Aquia Landing was surveyed at about el +8.6.

Physical impacts

The survey baseline at Aquia Landing runs along the top of a Jersey wall that separates the public beach from the adjacent access road. The road is about 0.6 m (2 ft) lower than the beach at the junction of the wall. Aerial imagery taken pre- and post-Isabel showed that enough sand, about 0.3 m (1 ft), overwashed the wall to completely cover the access road (Figure 15). The shift in shoreline position was mostly landward after Isabel. Typical bay beach profiles (Figure 16) show a cut and fill scenario while the tombolo beach in the lee of each breakwater unit were sheared down about 0.2 m (0.5 ft). Little or no scour existed in front of the breakwaters while slight infilling occurred in each embayment. A slight increase in elevation was measured on the river side of the

wall as the sand was moved up and over except where one scour hole occurred at the beach/wall junction. In addition, a reduction in vegetation in the lee of each breakwater occurred (Figure 17). The walkover to the beach was destroyed, and the bathhouse was flooded by the el 8.6 surge that covered everything at the site.

The overall change in topography of the site is shown in Figure 18. The yellow and orange areas on the isopach map indicate decreases in elevation of -0.2 m (-0.5 ft) and –0.3 m (-1.0 ft), respectively (Figure 18c). These areas occur in front and in the lee of each breakwater and along the beach berm zone of each embayment. Overall slight increases in sand elevation are shown in purple (+0.2 m (+0.5 ft) change), which occur intermittently along the backshore of each embayment and green (+0.3 m (+1.0 ft) change), which occur mostly along the very nearshore of each bay. No extreme changes (>0.3 m) (>1 ft) were measured in topography indicating the overall stability of the breakwater system.

Kingsmill

Isabel hydrodynamics

The Kingsmill south-facing shoreline is oriented approximately east-west allowing wind/waves from the southeast, south, and southwest to impact the site. Water levels were measured at Kingsmill by a tide gauge until about 2:30 p.m. on 18 September 2003 (Figure 14). During the storm, the gauge was damaged, and the last reading was about el 6.6 while tide was still rising. Wind and water level data also were measured at Sewells Point, which is about 23 n.m. downriver from the site. Wind speeds at Sewells Point exceeded 72.4 km/hr (45 mph) and remained so from 9:30 a.m. to about 5 p.m., and they reached sustained speeds of over 80.5 km/hr (50 mph) while water levels peaked at about 4 p.m. Kingsmill is located about halfway between Richmond and Norfolk, both of which have long-term wind monitoring stations. Wind data from Richmond shows more persistent winds from the north and northeast through the day on 18 September while Norfolk wind data showed winds more persistent from the east-northeast before they turned east then south. The combination of storm surge and southerly wind/wave climate, as indicated by the survey as the top of the bank scarping, resulted in water levels greater than el +10.2.

Physical impacts

Pre- and post-Isabel aerial imagery of the site show slight changes in shore position (Figure 19). Each tombolo apex had a tendency to shift upriver. Measurable base of bank recession occurred along much of the project, but it was particularly prevalent adjacent to each embayment. These changes are illustrated in the typical bay and breakwater profiles in Figure 20. The combination of storm surge and wave runup limits was measured in the field and are shown for each typical profile at just over el 10. This was a significant event for the site, yet overall damage was minimized by the heavily vegetated backshore/base of bank (Figure 21). Post-Isabel recovery is shown in Figure 19; the beach planforms have returned to approximately their pre-storm positions.

Topographic changes along the site between breakwater (BW) 3 and BW7 are shown in Figure 22. The isopach map that indicates a general pattern of reduction in elevation occurred along the beach, backshore, base of bank, and around each breakwater unit. Most increases in elevation were in the nearshore and in small pockets in the lee of each breakwater unit. The most severe scour occurred along the base of the bank (BOB) between BW5 and BW6. However, the damage did not endanger the integrity of the bank face. No slumping or failure was noted or has occurred since. Just upriver, extensive damage (more than $3 million) occurred at the adjacent marina, which only had a timber pile breakwater for protection.

Van Dyke

Isabel hydrodynamics

Sewells Point is the closet data station to this site; both wind and tide data are available through the entire storm event. Normal tidal lag for mhw between Sewells Point and the site is about 1 hr and 20 min. Although Sewells Point is the closest climatic station to the site, every indication is that conditions were more intense at Van Dyke than Kingsmill as evidenced by the severity of bank cut and limit of runup. Data from Richmond indicated that winds were more from the north and northeast throughout the day of 18 September while Norfolk data showed winds more persistent from the east-northeast before turning east then south. As a result of Van Dyke's north and northeast-facing shoreline, winds from the northwest, north, and northeast impacted this site. Wind speeds at Sewells Point got above 72.4 km/hr (45 mph) and remained so from 9:30 a.m. to about 5 p.m., and they reached sustained speeds of over 80.5 km/hr (50 mph). The wind direction at 9:30 a.m. was east-northeast and turned east by noon and southeast by 5 p.m. By interpolating between Richmond and Sewells Point, it would appear that Van Dyke had more of a northeast wind than indicated by the Sewells Point data.

Storm surge at Van Dyke at 9:30 a.m. was el +4.8, about el +6.0 by noon, and over el 8 by 5 p.m. The storm surge and northeast wind/wave climate combined to produce significant impacts to the site with wave runup measured to over el 10. The twin northeasters of 1998 produced storm surge of 2.3 m (7.5 ft) over two tidal cycles but with less sustained winds, peaking around 56.3 km.hr (35 mph). Wave modeling at the site (Hardaway and Gunn 1999b) predicts that for an 2.4-m (8-ft) surge and 112.7 km/hr (70 mph) wind from the northeast, a l.l-m (3.5-ft) breaking wave would be produced.

Physical impacts

Aerial imagery pre- and post-Isabel shows mostly landward shifts in the positions of both the shoreline and base of bank (Figure 23). Reduction in tombolo size are seen behind BW3, BW4, BW5, BW6, and also BW7, which had the narrowest attachment before the storm. The adjacent BOB along these structures also receded. Significant BOB recession also occurred in Bay A. General BOB stability is seen between BW2 and BW4 as well as between BW7

and BW8. These trends are shown in typical profiles for select bays and breakwaters (Figure 24). The combination of storm surge and wave height exceeded el 11, about 0.9 m (3 ft) higher than project design. Post-storm recovery shows the shore planforms have returned to approximately their pre-storm configuration (Figure 23).

Ground photos taken before and after Hurricane Isabel show the extent of the upland bank scarping by the combination of storm surge and wave impacts (Figure 25). The retreat of the BOB was generally more severe in the embayments than behind the breakwaters and associated tombolos. Also, BOB impacts were minimal where the interface between the backshore and BOB had a less steep gradient. This occurred where the banks had been mined for sand, at Bay B and Bay G.

The overall change in topography at this site is seen in Figure 26. Negative topographic changes are evident at each tombolo and around and in front of BW5, BW6, and BW7. Severe land reduction occurs along the aforementioned BOB and along the top of the downriver revetment. Consequent increases or no change in topography are generally greater in the nearshore areas as indicated by the pink patterns (0 m<change<0.3 m) (0 ft<change<1 ft).

Yorktown

Isabel hydrodynamics

Yorktown is located across the York River from VIMS where NOAA maintains the Gloucester Point tide gauge (Figure 14). During Isabel the gauge stopped at about 2:30 p.m. with a reading of about el +8.3 as the tide was still rising. Wind speed measurements at VIMS provided by instruments atop VIMS' Byrd Hall showed that maximum sustained winds on the campus reached 65 mph, with 144.8-km/hr (90-mph) gusts. The barometer bottomed out at 74.1 cm (29.2 in.), with a rainfall accumulation of about 5.6 cm (2.2 in.). At the height of the storm, VIMS' ADCP measured what might be considered a deepwater wave of 1.8 m (6 ft) with a 5 sec period. Still-water level at Yorktown was measured at el 8.6 (mean tide range is 0.7 m (2.4 ft)), and the combination of maximum storm surge and wave runup was measured at about el 12.5. One could infer that there could have been a 1.2 m (4 ft) or greater wave breaking across the breakwater system and into the adjacent infrastructure.

Physical impacts

Pre- and post-Isabel low-level aerial imagery show a narrowing of each tombolo and a landward shift of sand behind each breakwater unit (Figure 27). The shoreline position in the two middle and largest embayments showed only slight changes after the storm. Typical profiles show cross-sectional changes as a basic cut and fill in the embayments (Figure 28). Shearing occurred across the top of the tombolos as well. Some sand was lost to the offshore after the storm, but the county filled the beach to its pre-storm profile shortly after the hurricane. Post-storm recovery about 1 year later shows shore planforms to have returned to their pre-storm position. A noticeable shore advance is seen in Bay B and D.

Sand was carried into the adjacent street, but recent granite block backstops helped reduce this tendency. These blocks measuring about 0.3 m (1 ft) square, 1.5 m (5 ft) long, and weighing about 907.2 kg (1 ton) were easily shifted around by the storm waves. Several areas of scour occurred along the backshore/ sidewalk/road juncture (Figure 29), but post-storm cleanup and added fill restored the public beach to use by late October 2003. The businesses along the waterfront were severely damaged. It took several months for their rehabilitation due to water damage, but they are presently operating. Figure 30 shows a low backshore along Water Street in Yorktown as well as the storm wrack lines, which are the floating debris accumulated at the limit of high water. At Colonial National Historical Park, just downriver from Yorktown, small rocks from the revetment along the shoreline were scattered on the road, and the adjacent upland bank was severely scarped.

7 Discussion

Aquia

Aquia Landing was the least impacted by Hurricane Isabel of the four sites discussed in this report. It had the least storm surge and it was not directly impacted by wave attack. Nevertheless, the storm impacts were enough to carry sand into the access road due to the low backshore and the absence of an upland bank. However, no significant infrastructure was damaged at the site. Overall, this site fared well with little or no impact.

Just downriver at two other sites which had no shore protection system, significant change occurred (Figure 31). Dahlgren is on the south side of the Potomac River just downriver from the Route 301 Potomac River Bridge. Its bank was eroded 4.6 to 6.1 m (15 to 20 ft) threatening upland infrastructure (Figure 32). On the north side of the Potomac River, Lenhart is slated for development. During the storm, its bank retreated 3.0-4.6 m (10-15 ft) (Figure 33).

Kingsmill

At Kingsmill, the high banks and high end infrastructure posed a significant problem for long-term shore protection. The design had considered these factors so performance expectations were high. The headland breakwater system performed beyond expectations. The storm surge and wave action overtopped the system, but impacted a heavily vegetated backshore/base of bank area causing minimal bank scarping, which posed no threat to the integrity of the graded bank face.

Just up the James River along the National Park Service's Colonial Parkway, significant retreat occurred to the unprotected bank (Figure 34). The higher bank at the Confederate Fort had scarping leading to the loss of trees along the waterfront. Farther upriver in the open area adjacent to the parkway, in areas where the bank was not sloped, scarping and retreat occurred. However, where the upland is graded to water interface, only minor scarping occurred.

Van Dyke

Hurricane Isabel exceeded the design conditions at the site, but it is difficult to accurately quantify its hydrodynamic forces. All of the piers along the shore sustained significant damage, and although the base of the bank was cut along

most of the site, no banks failed or incurred significant damage. The banks will be regraded and a wider backshore will provide a larger buffer between the banks and storm waves once the vegetation is restored. No significant alteration in beach planform or loss of sand from the system occurred. The breakwater system is stable.

Both Kingsmill and Van Dyke have high graded banks adjacent to the breakwater/beach system that interface at about el +7 for each site, which is the elevation of a 50-year return interval storm. During Hurricane Isabel, the combination of storm surge and wave height impacted the banks to over el +10 at both sites. Kingsmill had a much denser vegetated backshore and was able to withstand wave attack better than areas of Van Dyke. The Van Dyke site is more exposed because of its orientation, causing bank cutting in the embayments in front of the steeper bank areas. Areas with a gentler grade at the beach/base of bank interface had little or no bank scarping. Isabel exceeded the design level for each site.

Near Van Dyke on the James River, other sites did not fare as well. Just downriver from Van Dyke, a revetment at the east end of the site was overtopped by the storm surge and waves (Figure 35). No erosion occurred of the graded bank just upriver from the revetment where the beach is wide behind a headland breakwater. The revetment crest elevation is +8 ft mllw. Mogarts Beach, a few miles downriver on the James, suffered severe erosion of the beach and bank, a loss of over 6.1 m (20 ft) in places, such that a road is now threatened (Figure 36). The narrow beach and low revetment offered little protection to the shoreline.

Yorktown

The waterfront at Yorktown was severely damaged by Hurricane Isabel. The low backshore and adjacent low bank allowed the storm surge to inundate the structures protected by the project. However, the wave action was significantly reduced by the public beach's breakwater system, which may have spared the structural integrity of the buildings located along Water Street. This system experienced sand losses and local scour but maintained its overall integrity and performed above expectations; the system was designed for a 50-year event and sustained what many consider a 100-year event in this part of the bay.

Approximately 2.4 km (1.5 miles) downriver from the Coleman Memorial Bridge, also on the south side of the York River, the National Park Service maintains the Moore House, a historic landmark. Their 487.7 m (1,600 ft) of shore has a general west-northwest to east-southeast orientation and is exposed to the Chesapeake Bay from the northeast. Water depths are relatively shallow with the 3.7-m (12-ft) contour approximately 243.8 m (800 ft) offshore, and waters deeper than 11 m (36 ft) is 610 m (2,000 ft) offshore. The upland shore areas have 9.1 to 12.2-m (30 to 40-ft) mostly vertical cliffs with interspersed ravines. The elevation of the revetment is about el +6. Significant scarping occurred above the revetment and along the section of shore that was unprotected with bank recession of about 1.5 to 3 m (5 to 10 ft) (Figure 37).

8 Conclusions

The four breakwater sites assessed for this report performed very well under the direct impacts of high water and waves produced by Hurricane Isabel. All systems were 0.6 to 1.2 m (2 to 4 ft) under water with an additional 0.6 to 0.9 m (2 to 3 ft) waves breaking across what was the surf zone during the storm. Aquia and Yorktown were completely overtopped as waves attenuated across the breakwater system and impacted the low backshore and adjacent upland. Maintenance at each site only required returning the sand to the beach from the adjacent road. Yorktown required about 764.6 cu m (1,000 cu yd) of sand to fill in the scour holes along the backshore/side walk intersection.

The Kingsmill and Van Dyke breakwaters systems had the task of reducing storm wave attack against high upland banks and preventing catastrophic scour and bank failure. Each system performed well, and the results indicate that a less steep gradient between backshore and the bank face greatly reduced the potential for bank scour. Also, a heavily vegetated backshore/base of bank interface may greatly reduce bank scour. The only post-storm maintenance to the banks that had to be performed was regrading several areas at Van Dyke. No additional sand fill was required at either site. No structural damage occurred to breakwater units at any site.

There is always a discussion of costs vs. benefits for any type of shore protection. The fact is that well built stone walls at el +8 were overtopped and the adjacent upland scarped. The advantage or desirable element with headland breakwaters is that comparable or better shore protection is attained with a stable beach system that remains intact after the event. Higher breakwaters and more sand would give more protection, but would cost more.

The significance of the hurricane and the minor damages occurring at each site shows that headland breakwater systems offer effective shore protection with the benefits of beach and dune habitat. The post-storm recovery is also important and shows the durability of the designed beach planforms.

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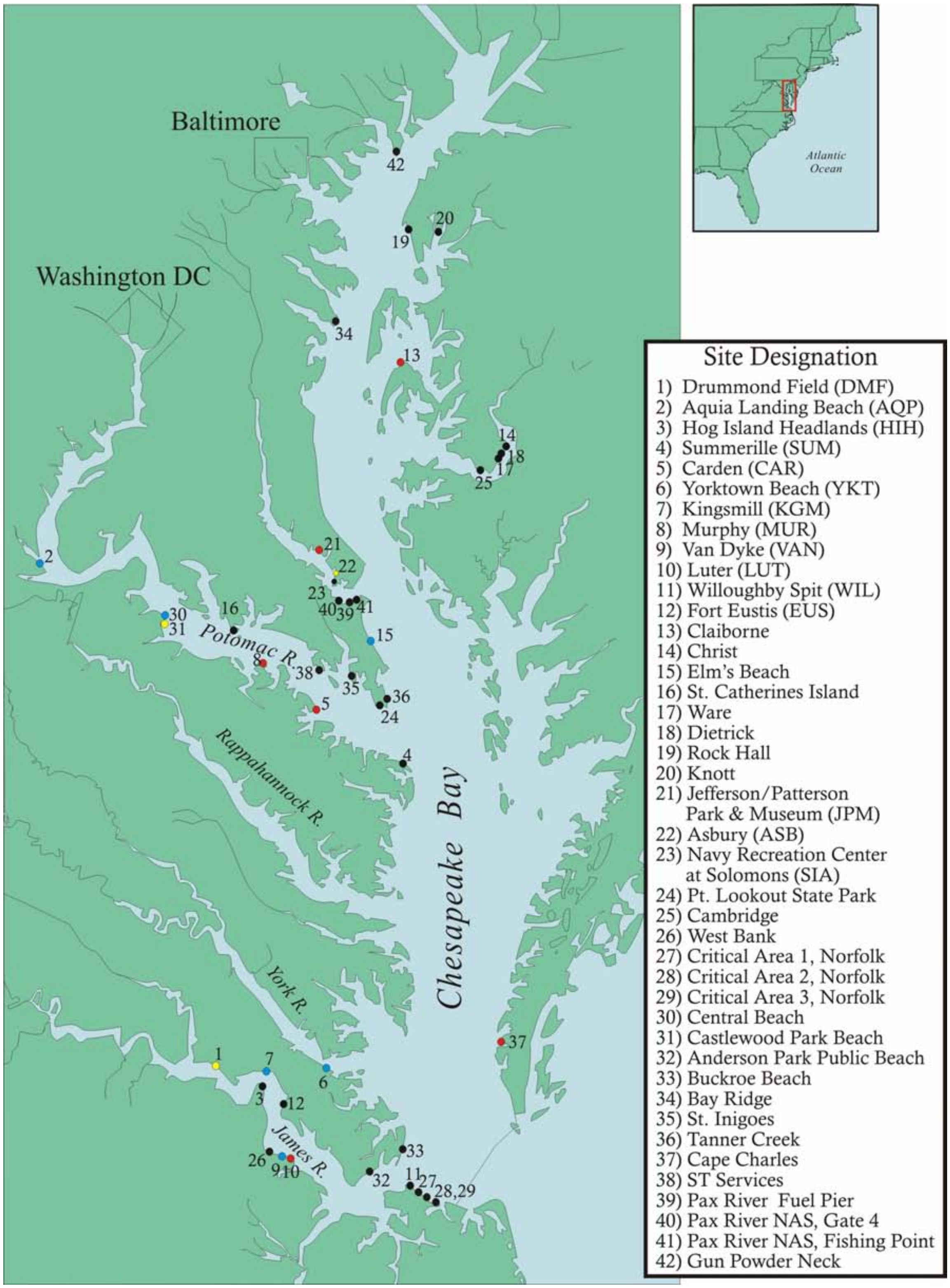


Figure 1. Location of breakwater sites throughout Chesapeake Bay. Post-Isabel survey sites are shown in blue; 2003 survey sites are shown in yellow; and 2004 survey sites are shown in red

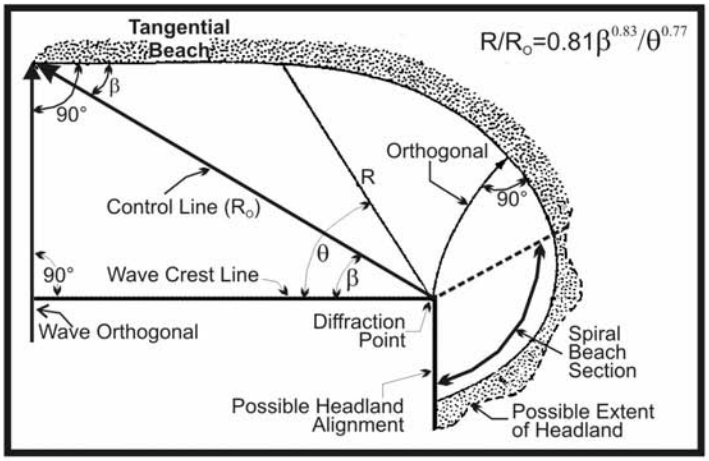


Figure 2. Parameters of Static Equilibrium Bay (after Hsu et al. 1989)

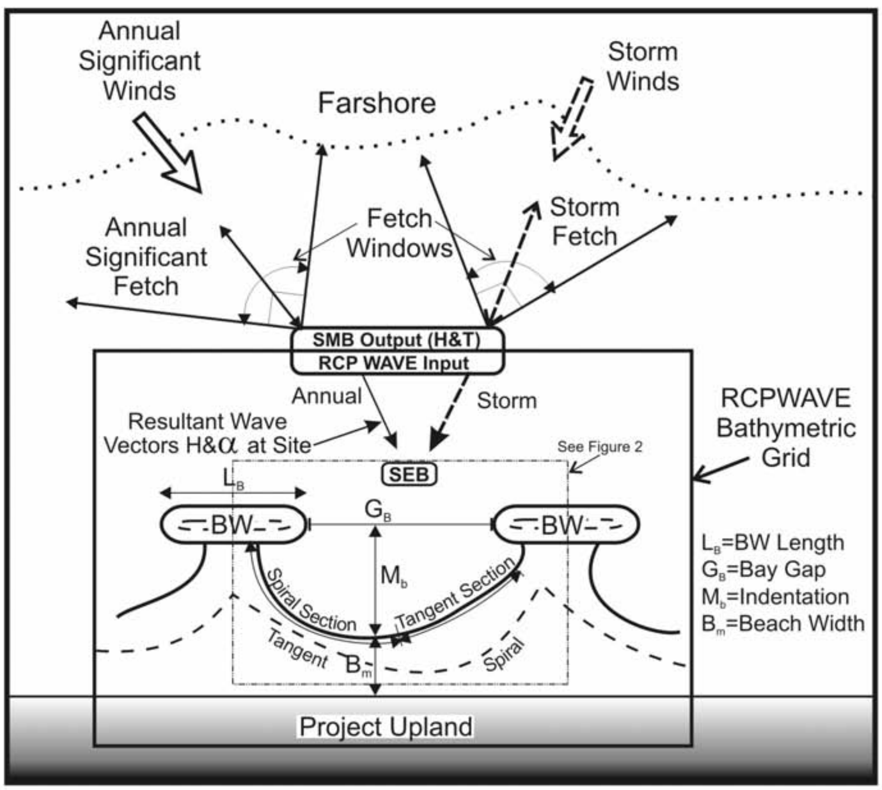


Figure 3. Parameters related to wind/wave generation (SMB), nearshore wave
refraction (RCPWAVE), and beach planform predication (SEB)

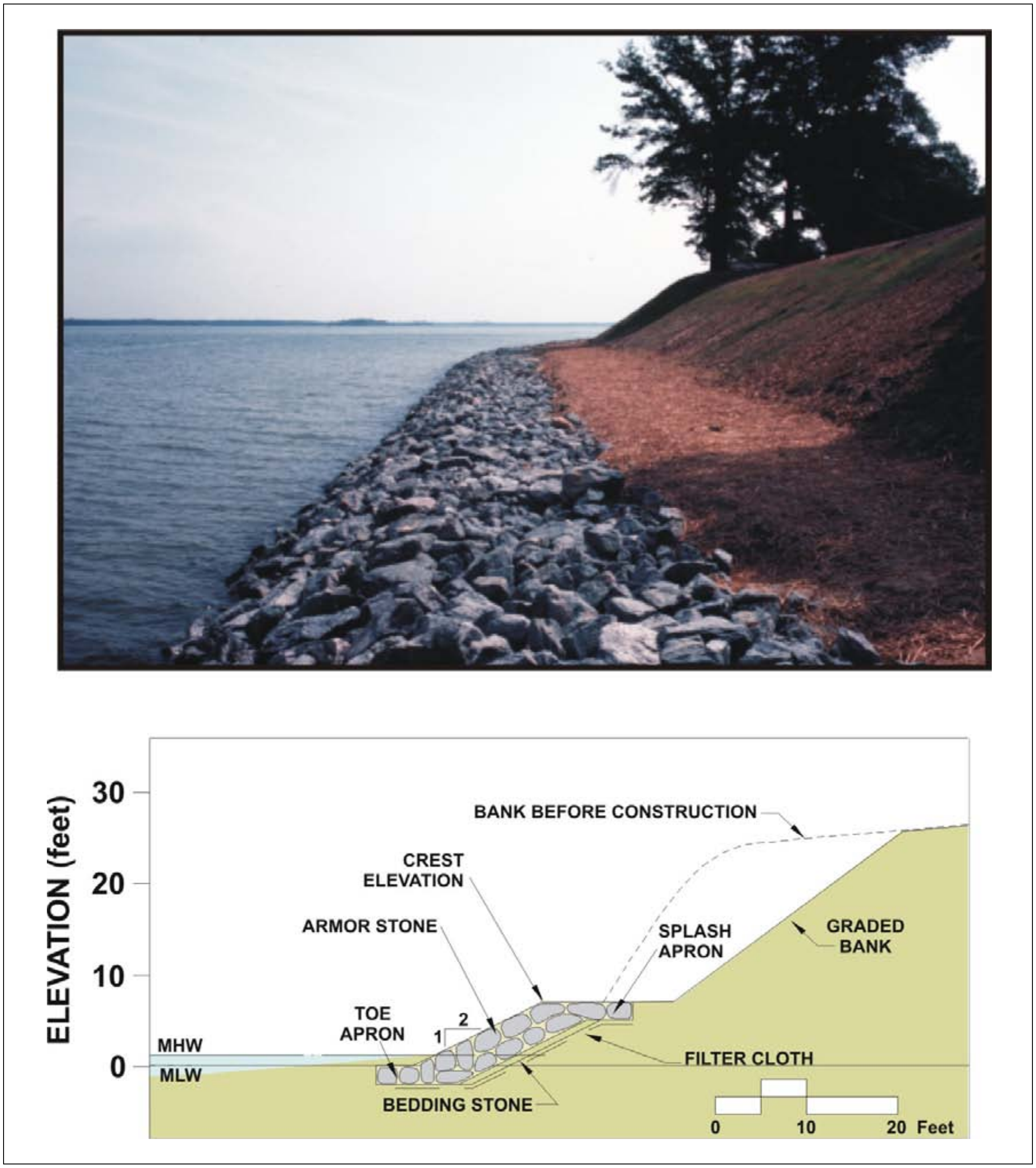


Figure 4. Stone revetment shortly after construction on Potomac River, VA; and cross section of elements necessary for proper stone revetment design. There are usually two layers of armor stone over a bedding stone layer with filter cloth between earth subgrade and bedding layer. Armor size depends on design wave height which is determined from an analysis of wave climate for each project site (Hardaway and Byrne 1999)

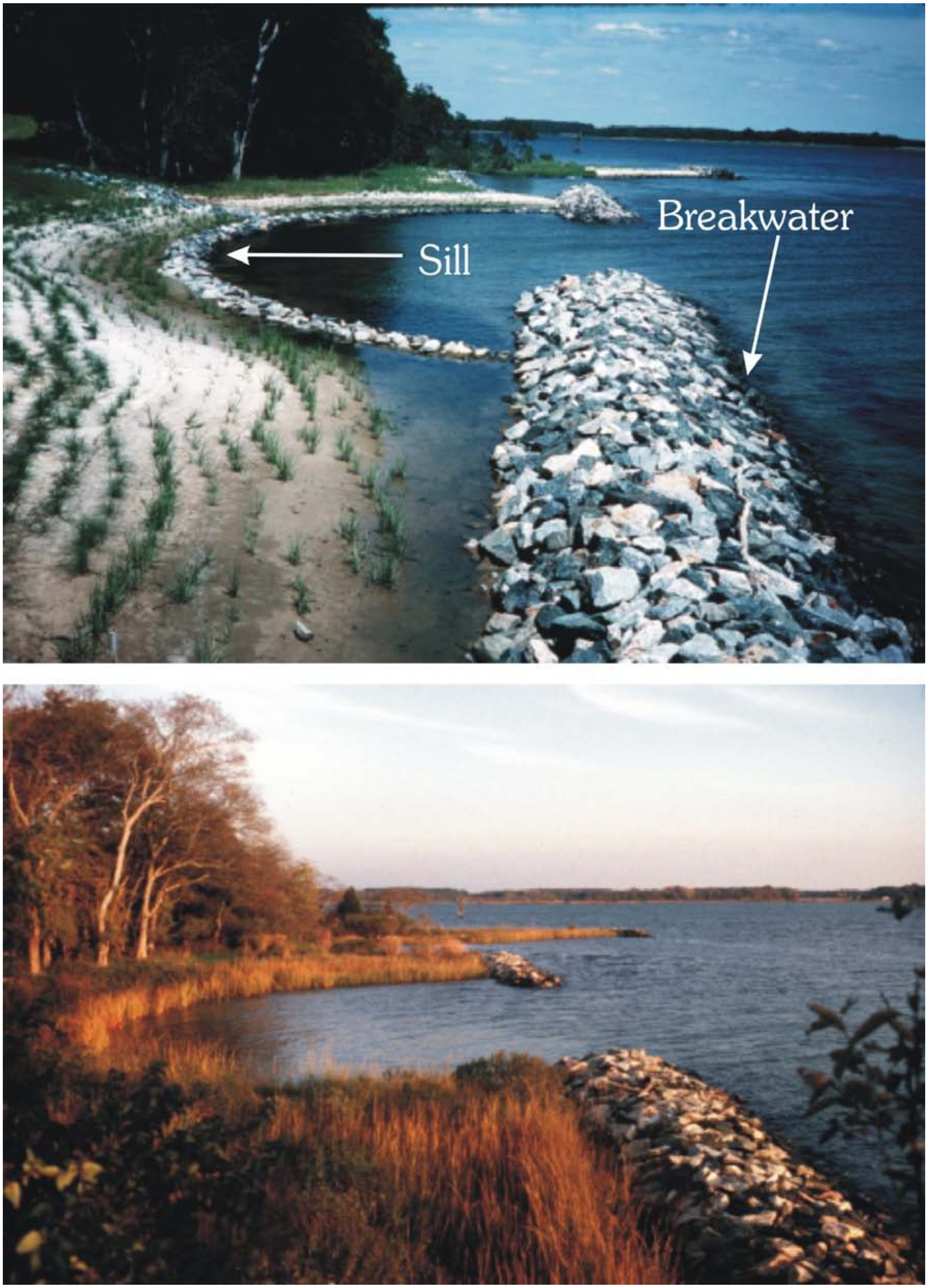


Figure 5. Stone sill connecting breakwaters with sand fill and marsh implantation on Choptank River, Talbot County, MD, just after construction and 5 years post-construction (Hardaway and Byrne 1999)

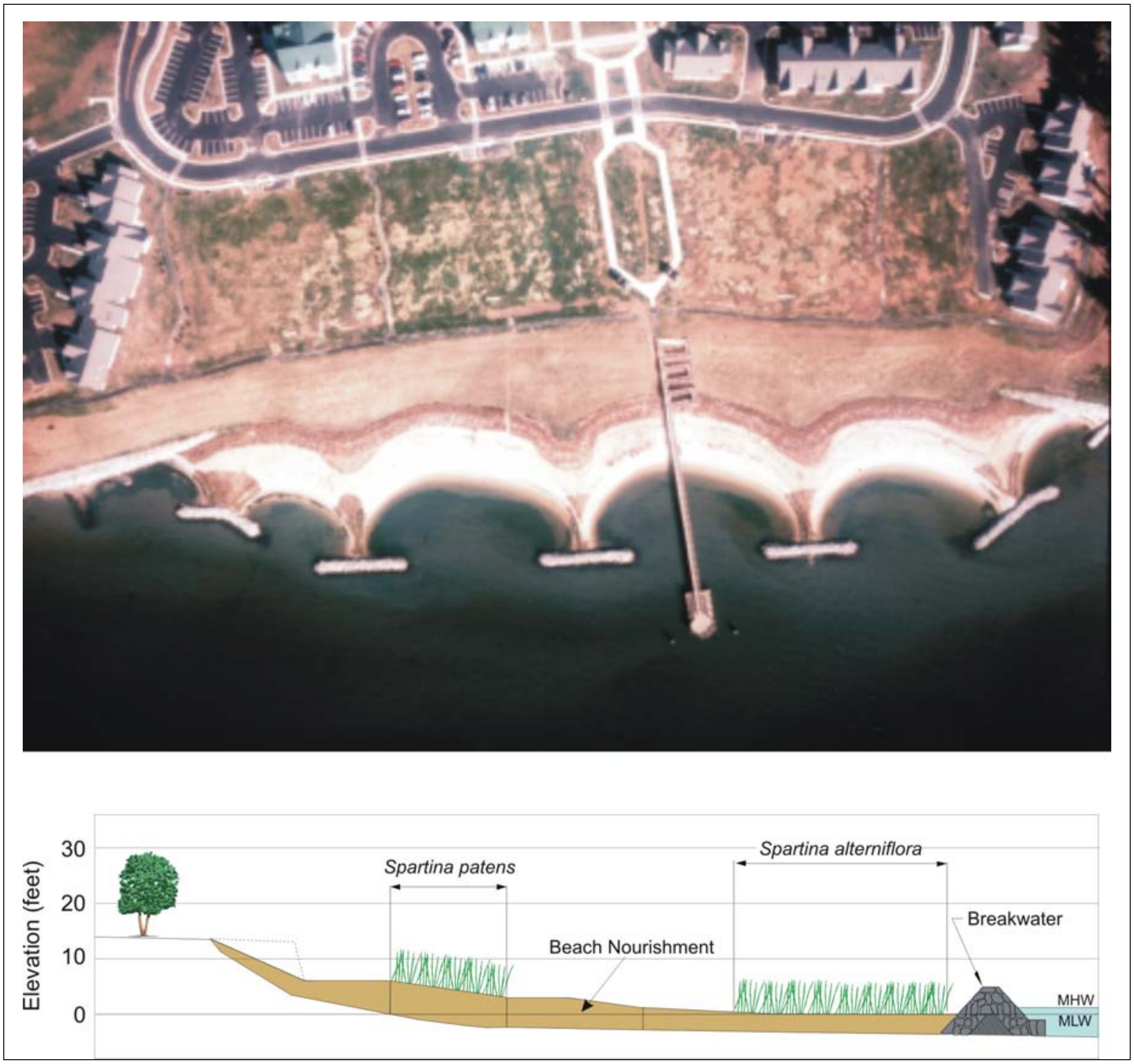


Figure 6. Breakwater system on Patuxent River in Calvert County, MD, and a typical breakwater cross section

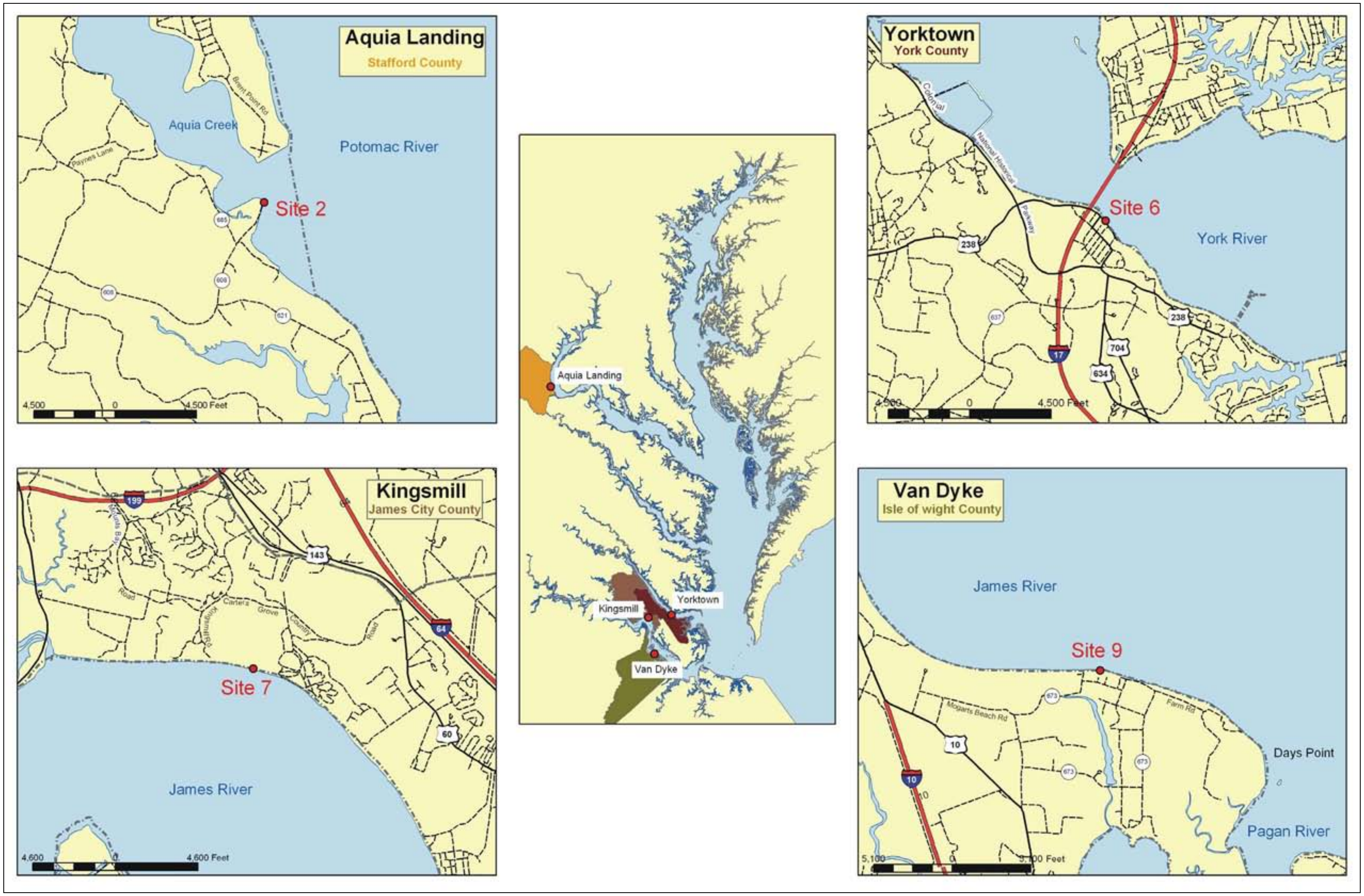


Figure 7. Location of surveyed breakwater sites analyzed for this report

a. Before installation of breakwaters on ground and aerially

b. After installation of breakwaters

Figure 8. Aquia Landing

a. Before installation

b. After installation

Figure 9. Kingsmill

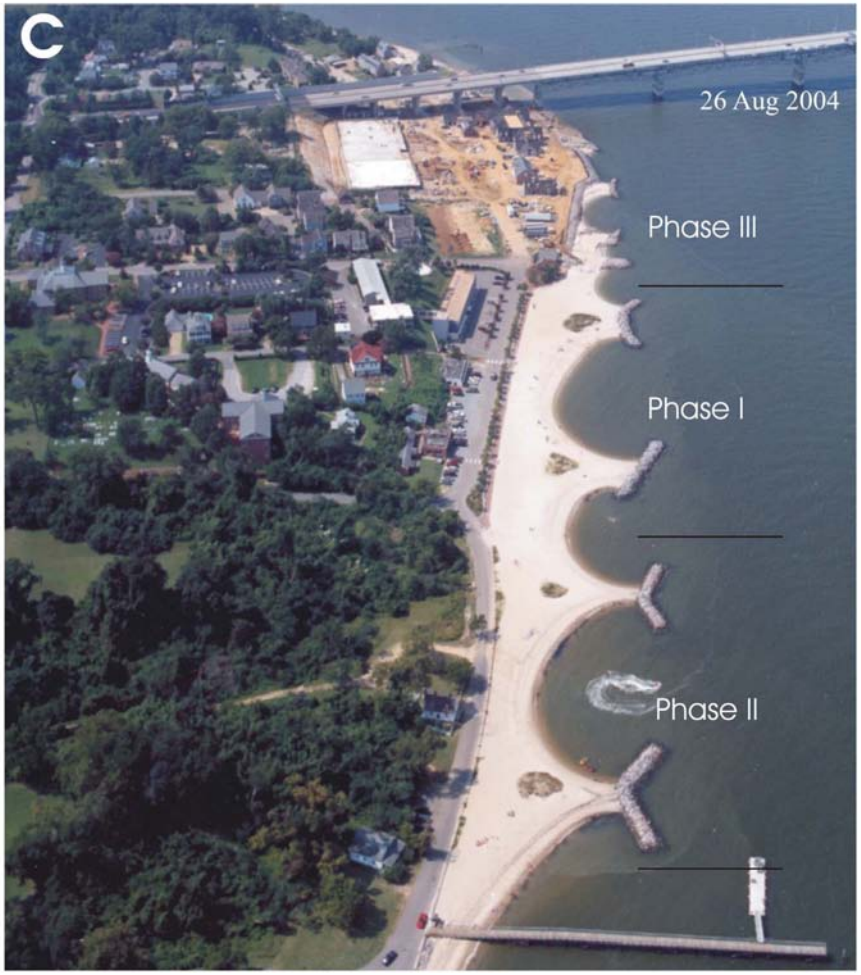
a. Before installation

b. After installation

Figure 10. Nonrectified aerial photography of Van Dyke

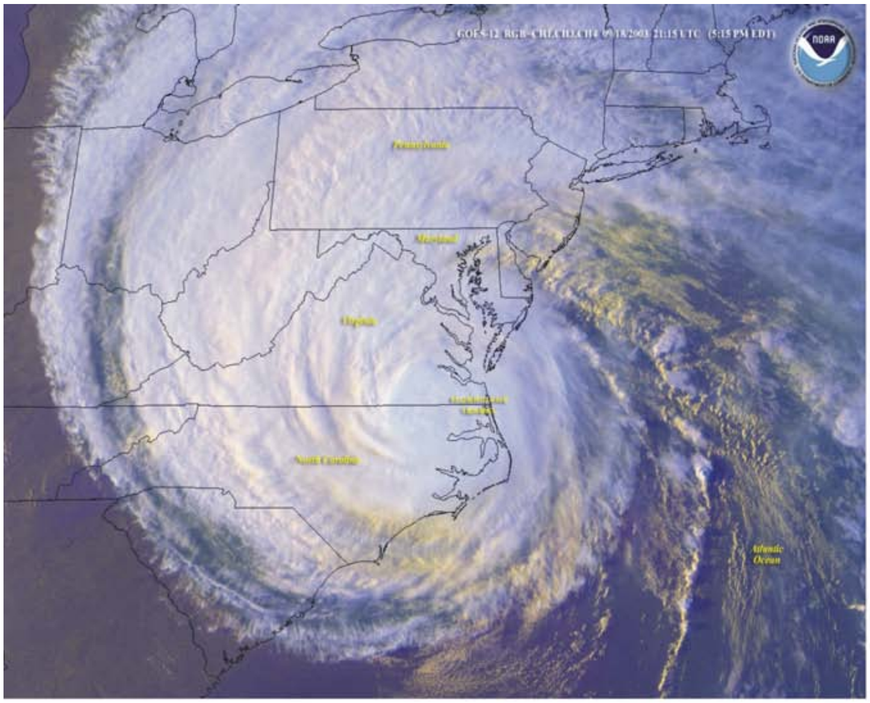
a. Before installation of any shore management structures

b. After installation of a revetment and small breakwater



c. After Phase III breakwater construction

Figure 11. Aerial photographs of Yorktown



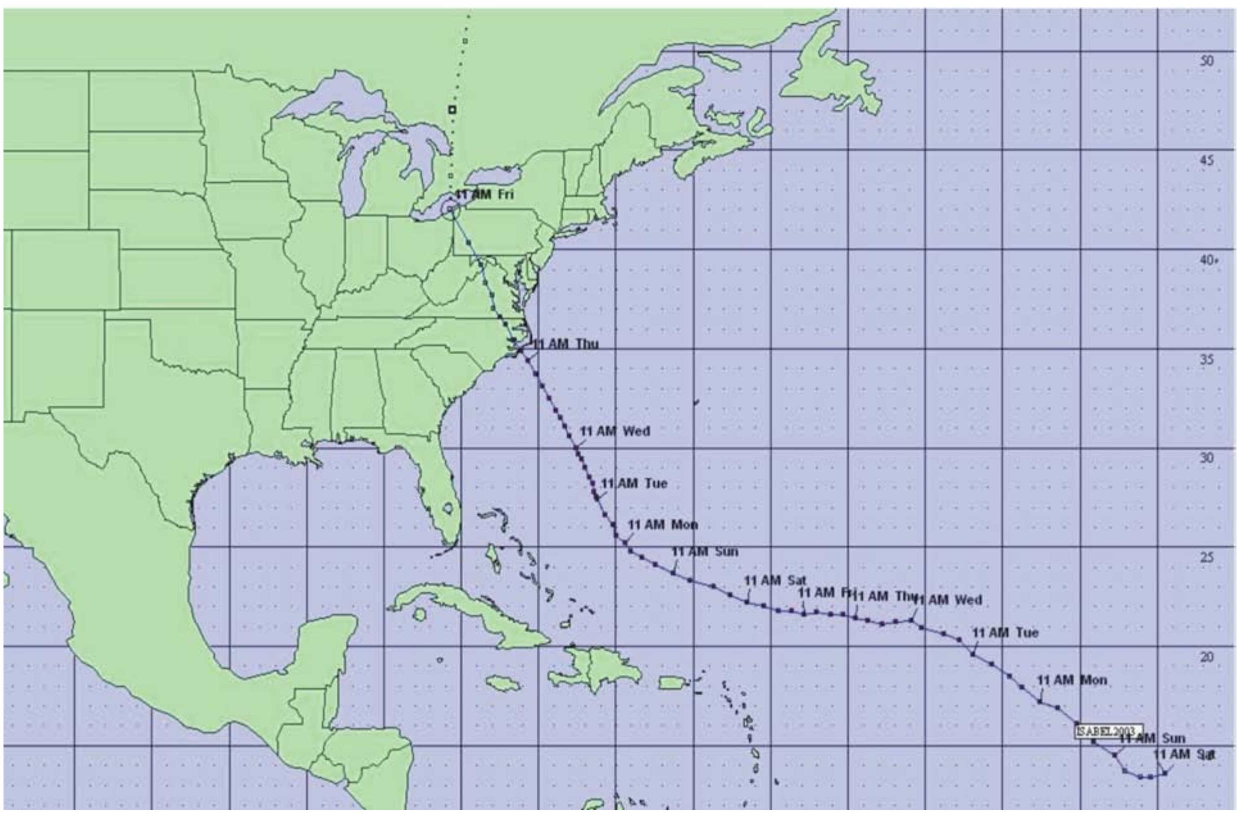


Figure 12. Hurricane Isabel photograph at landfall and storm track from the National Hurricane Center

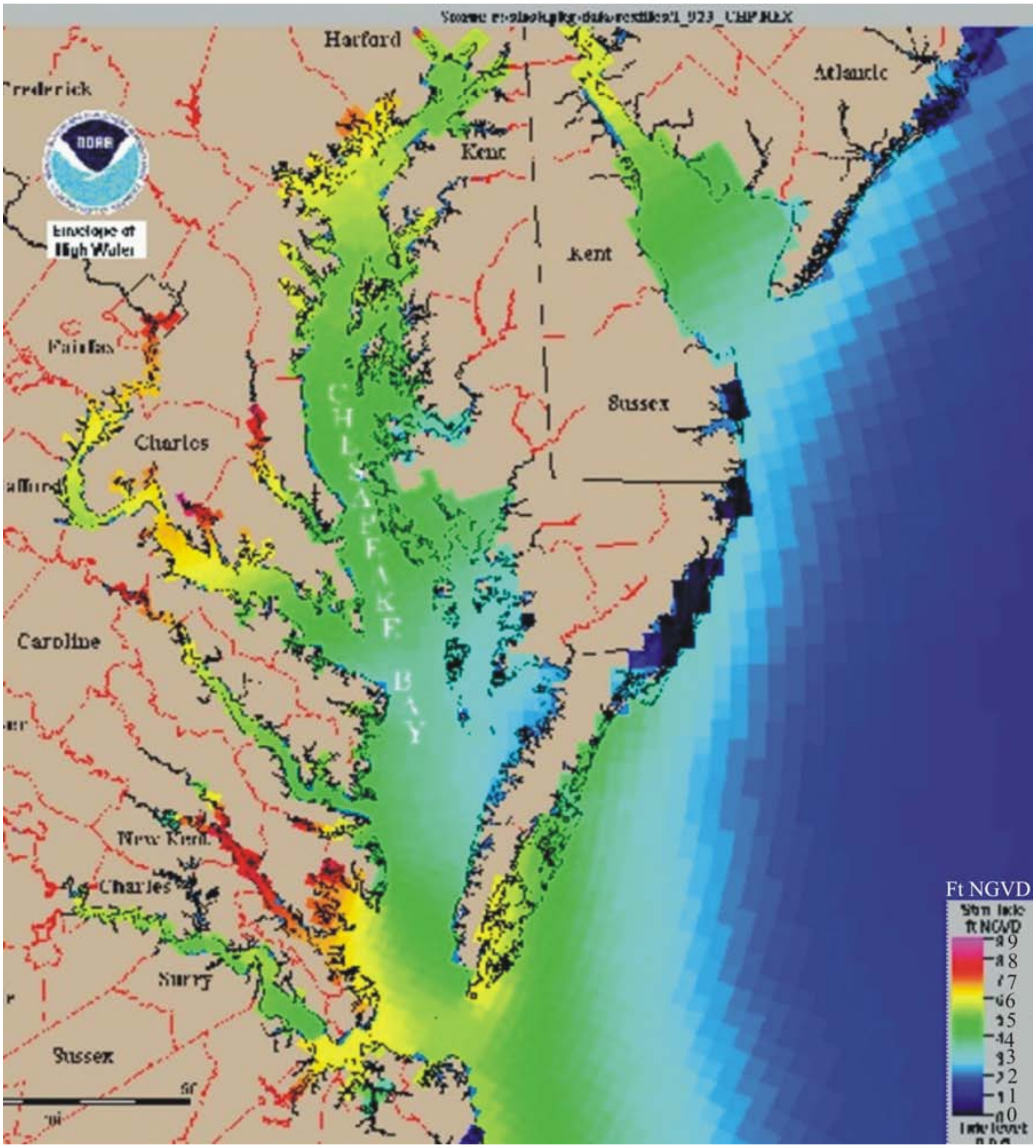


Figure 13. NOAA's slosh model storm surge prediction of Chesapeake Bay for Hurricane Isabel

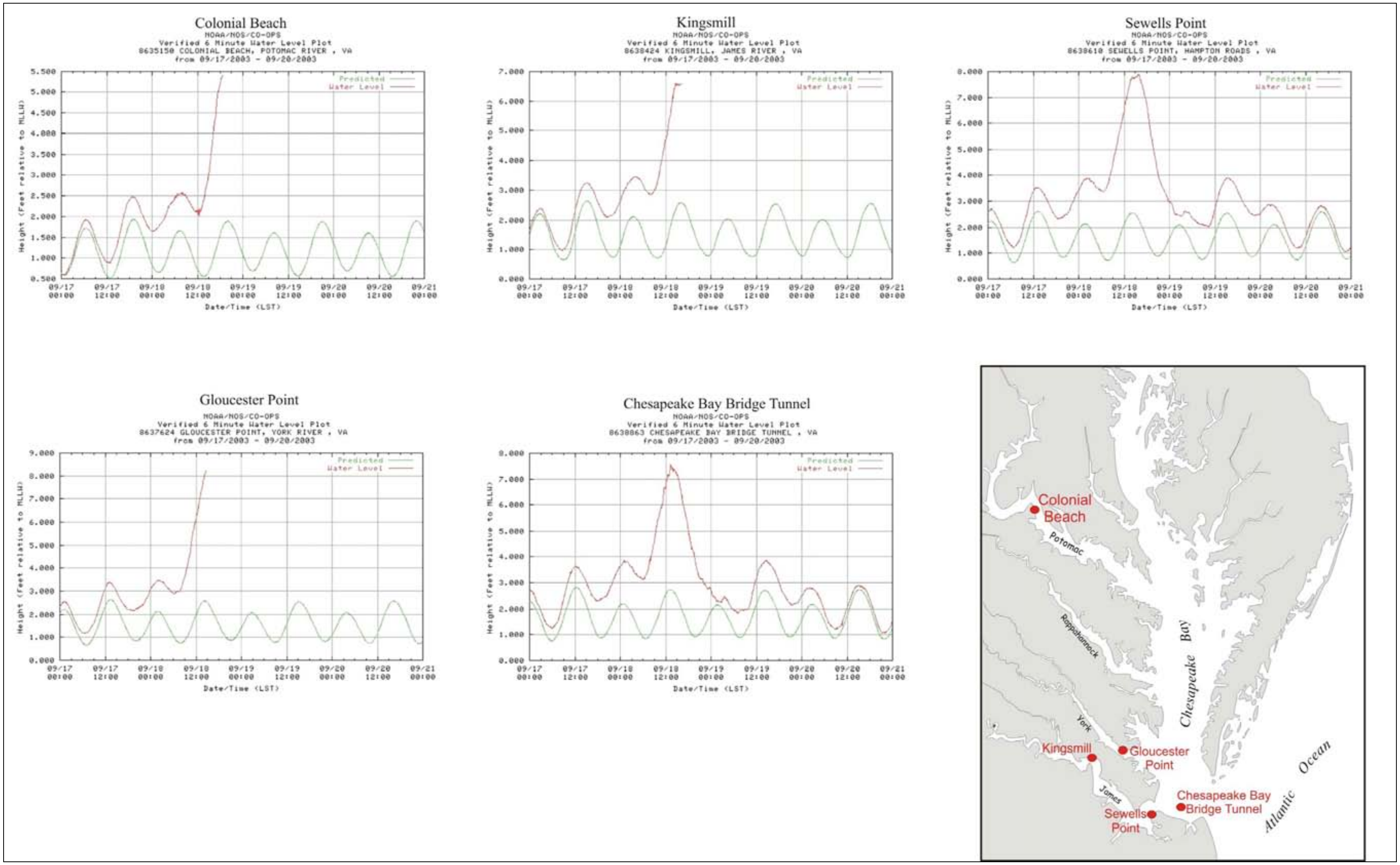


Figure 14. Verified water levels at wave gauges around Chesapeake Bay during the storm and approximate gauge location. From the NOAA Web Site (http://www.co-ops.nos.noaa.gov/)

Figure 15. Aquia Landing low-level pre- and post-Hurricane Isabel ortho-rectified aerial photographs

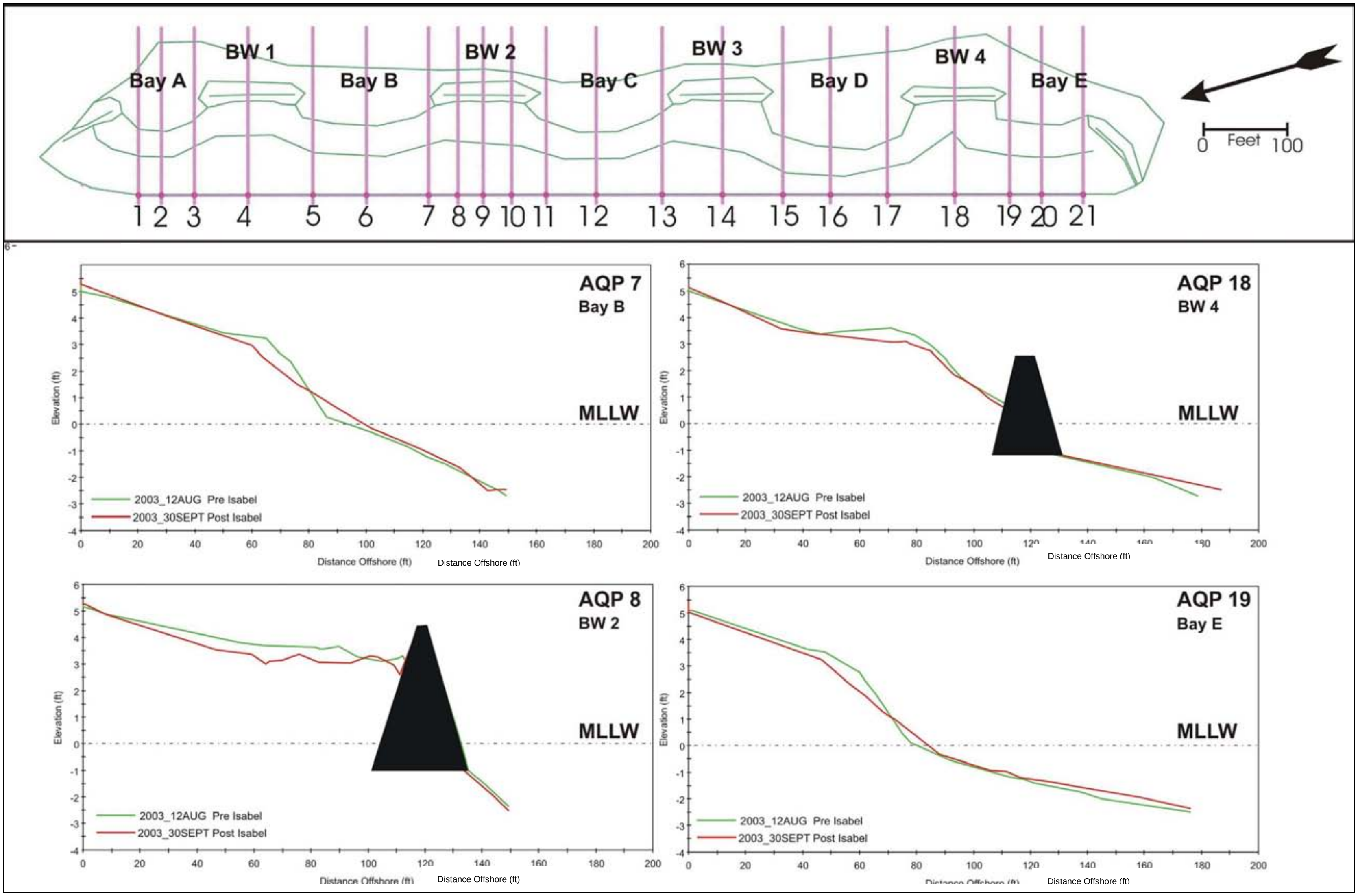


Figure 16. Aquia Landing (AQP) baseline and selected pre- and post-storm cross sections

a. Looking south along Jersey wall and access road

b. Looking north from BW 2

Figure 17. Aquia Landing ground photographs pre- and post-Hurricane Isabel

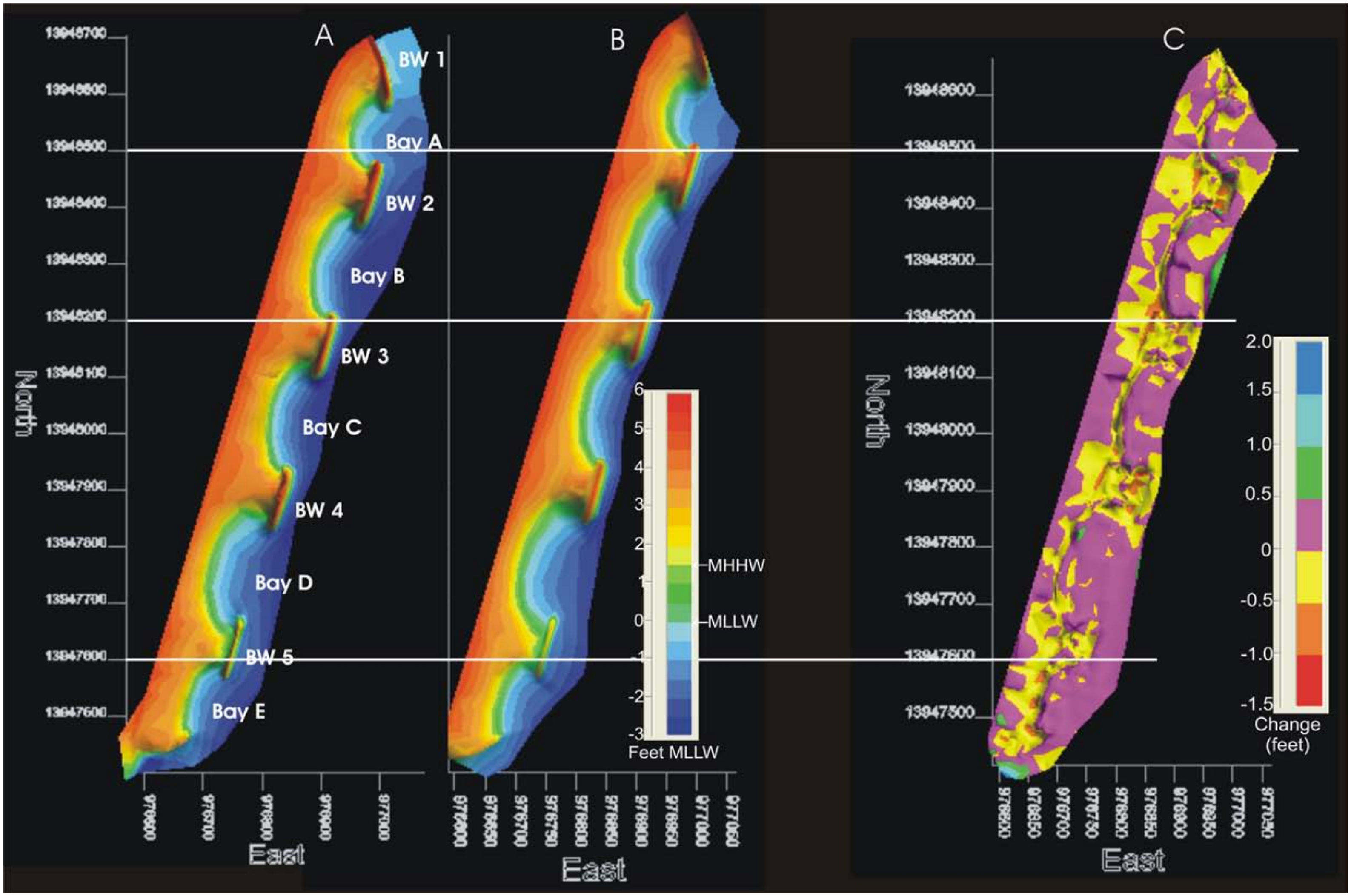


Figure 18. Aquia Landing color contour maps for: (a) pre- and (b) post-storm conditions, and (c) isopach map showing elevation changes between surveys

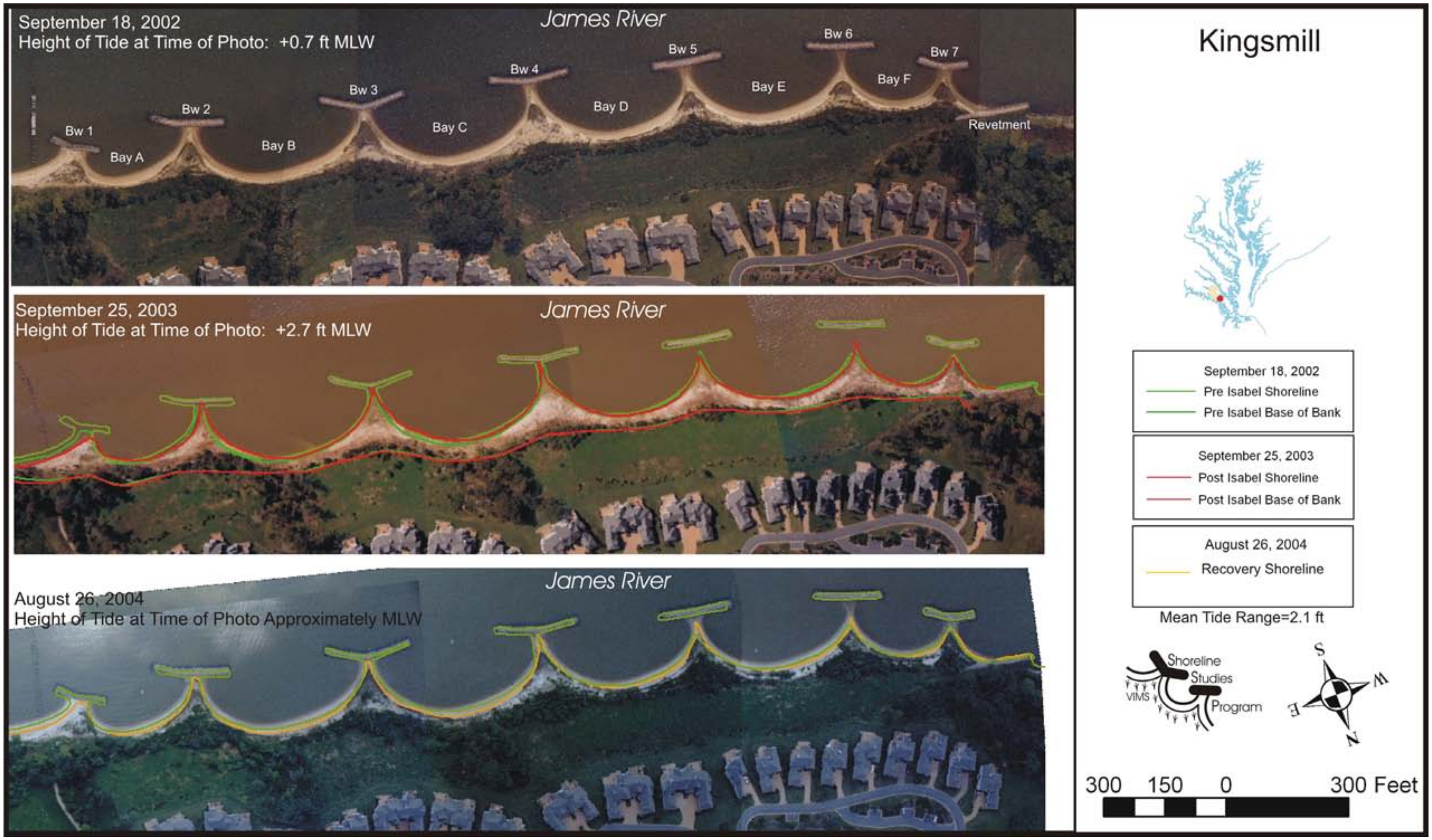


Figure 19. Kingsmill low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photographs

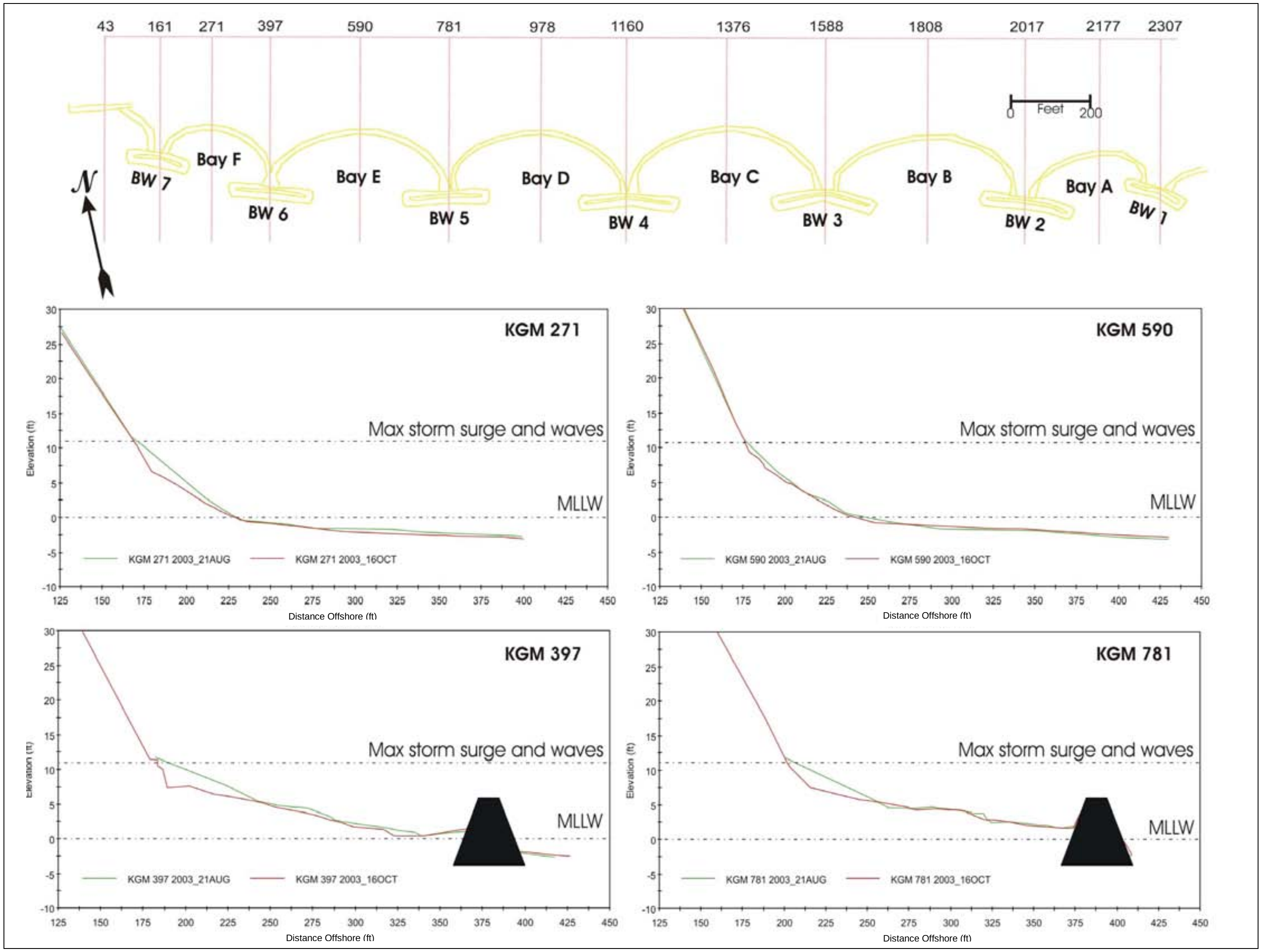


Figure 20. Kingsmill (KGM) baseline and selected pre- and post-storm cross sections

Figure 21. Kingsmill ground photographs before and after Hurricane Isabel

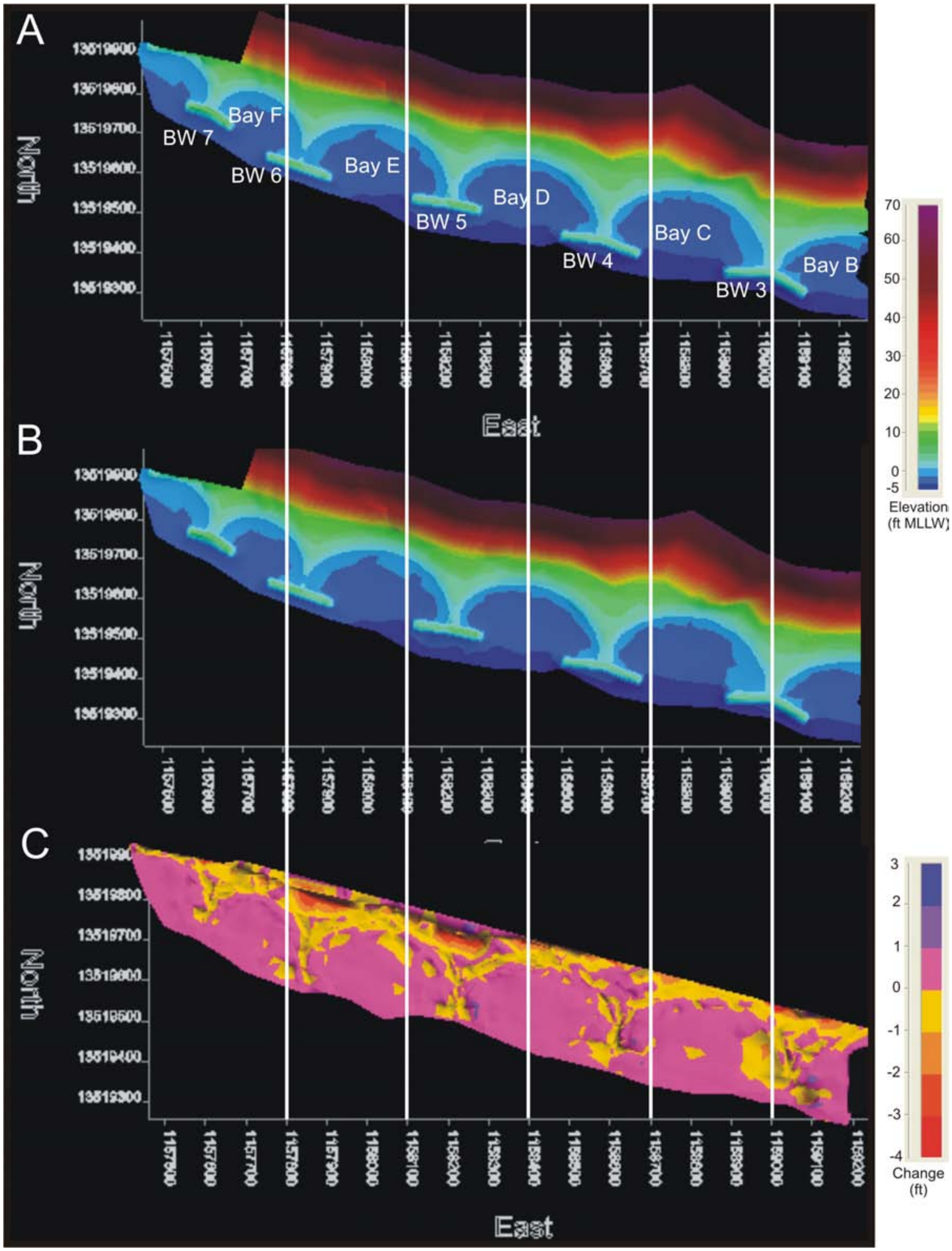


Figure 22. Kingsmill color contour maps for: (a) pre- and (b) post-storm conditions, and (c) isopach map showing elevation changes between surveys

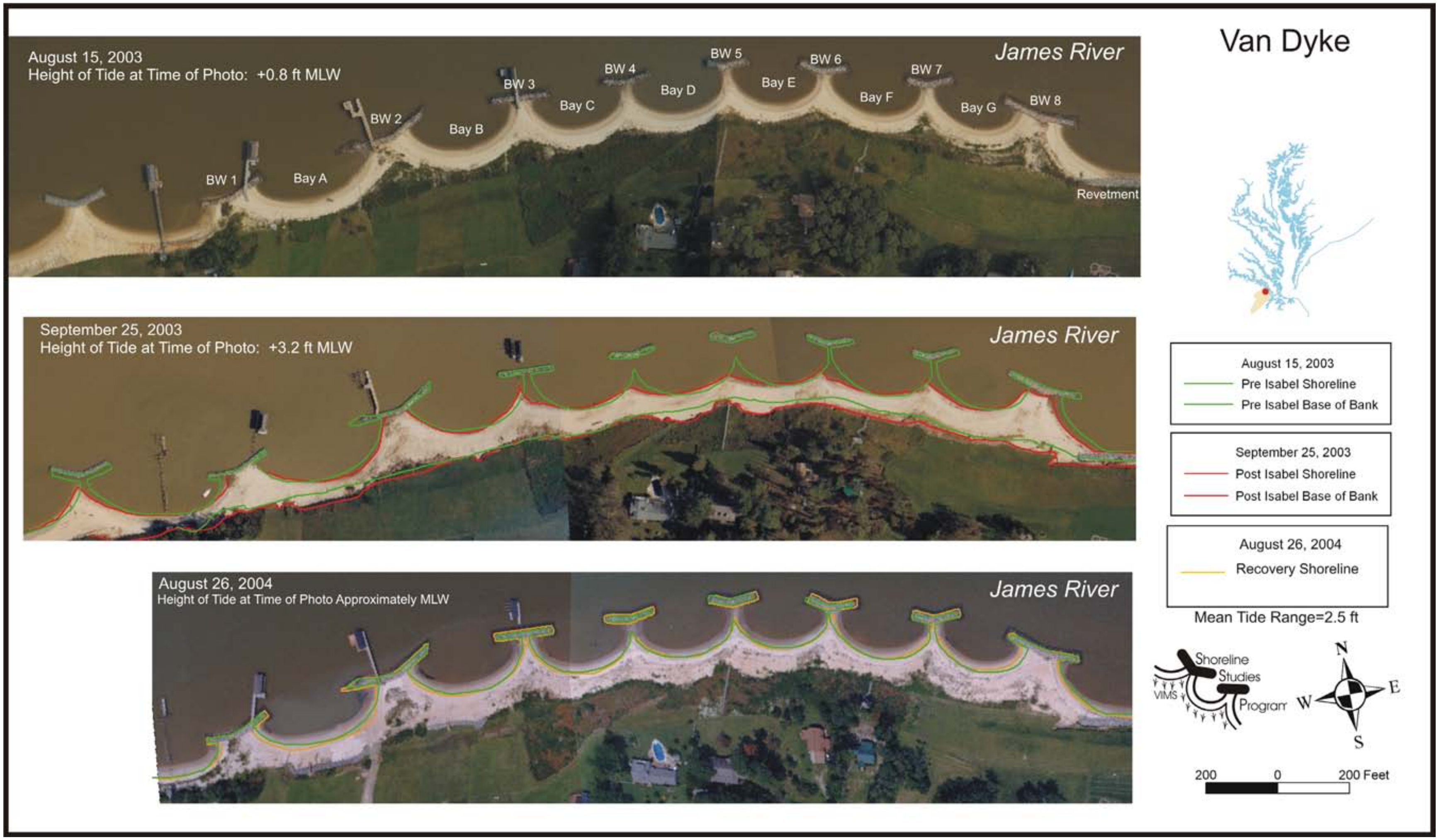


Figure 23. Van Dyke low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photographs

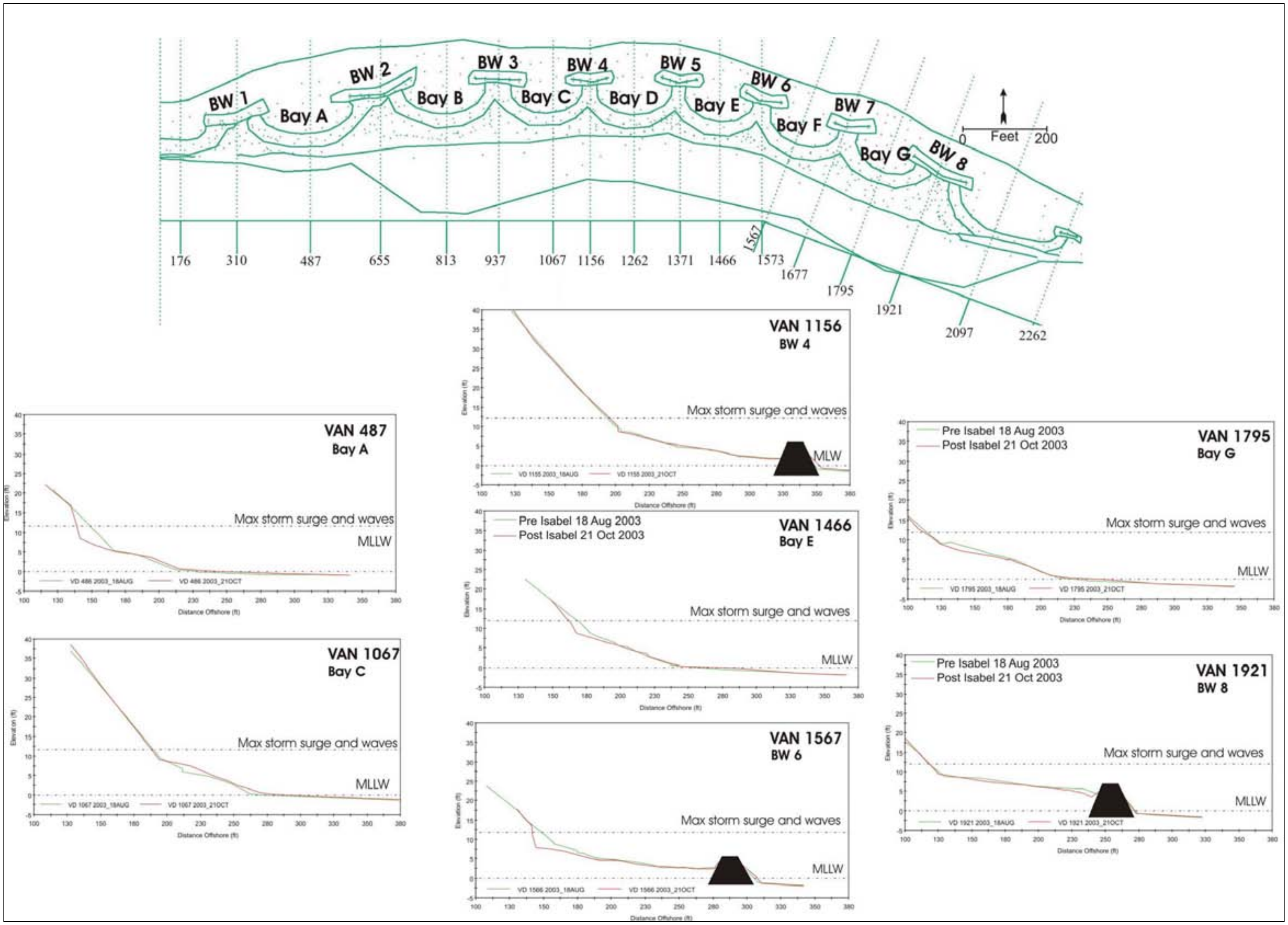


Figure 24. Van Dyke (VAN) baseline and selected pre- and post-storm cross sections

Figure 25. Van Dyke ground photographs before and after Hurricane Isabel

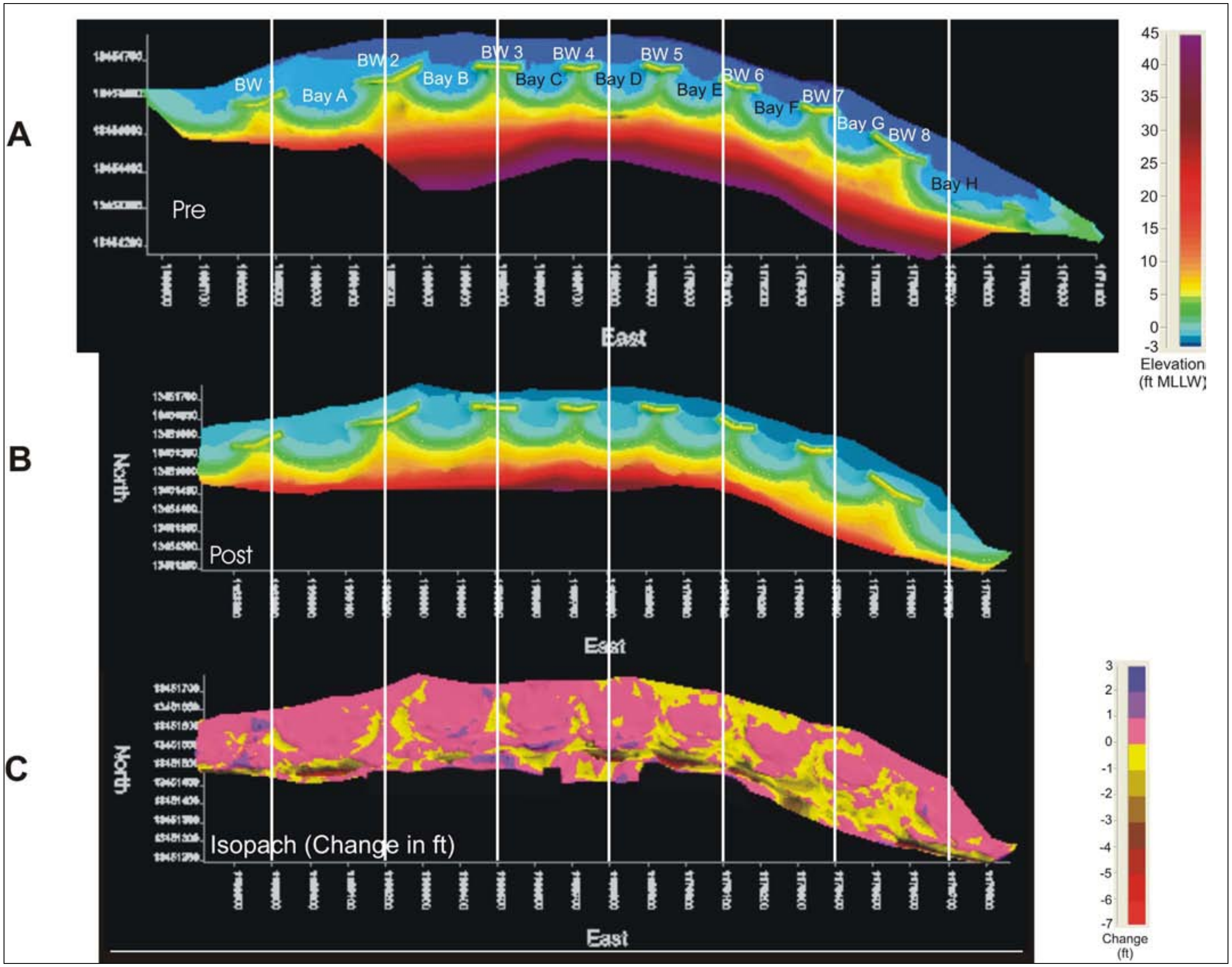


Figure 26. Van Dyke: (a) pre- and (b) post-storm color contour maps, and (c) isopach map showing elevation changes between surveys

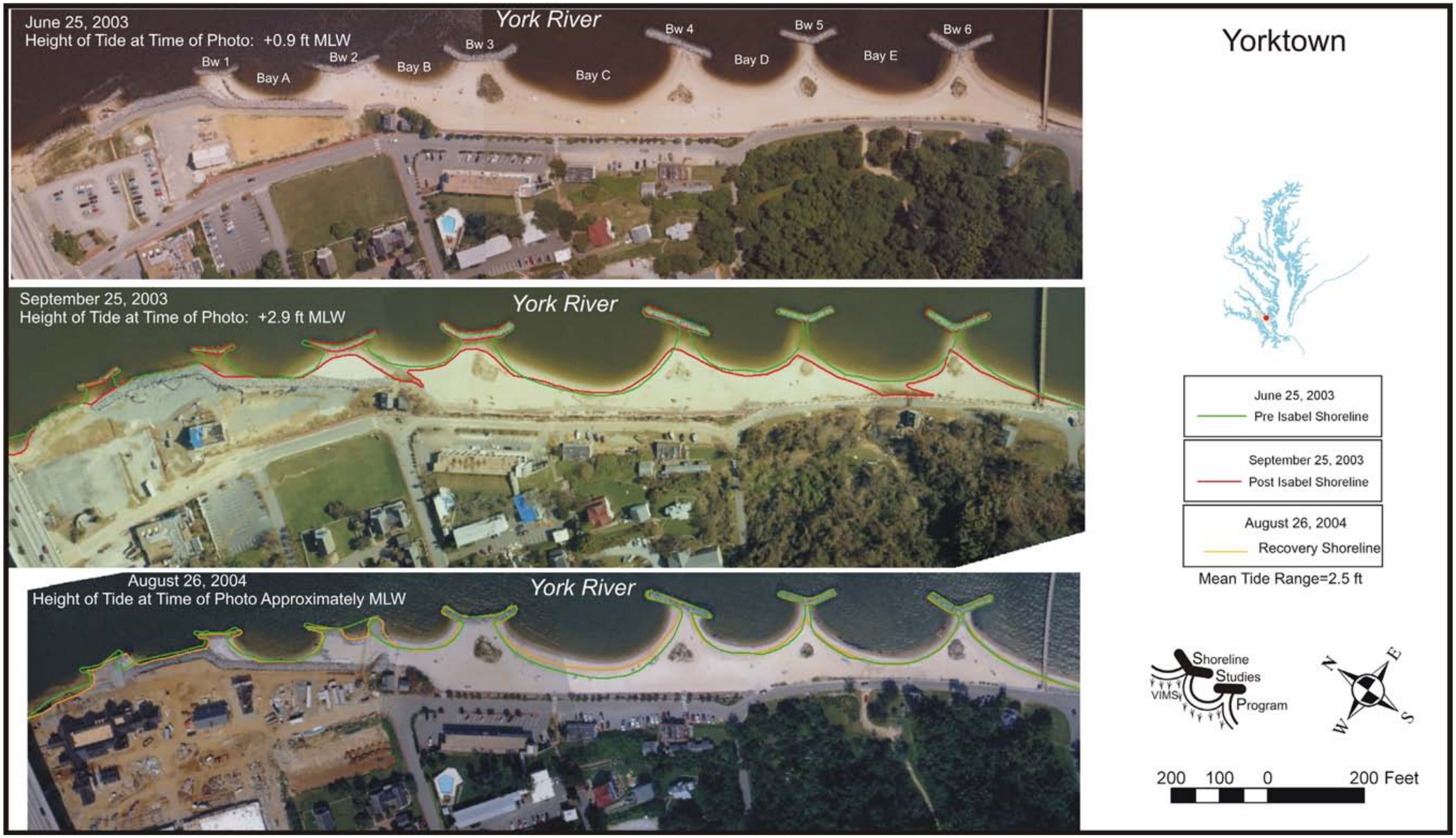


Figure 27. Yorktown low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photographs

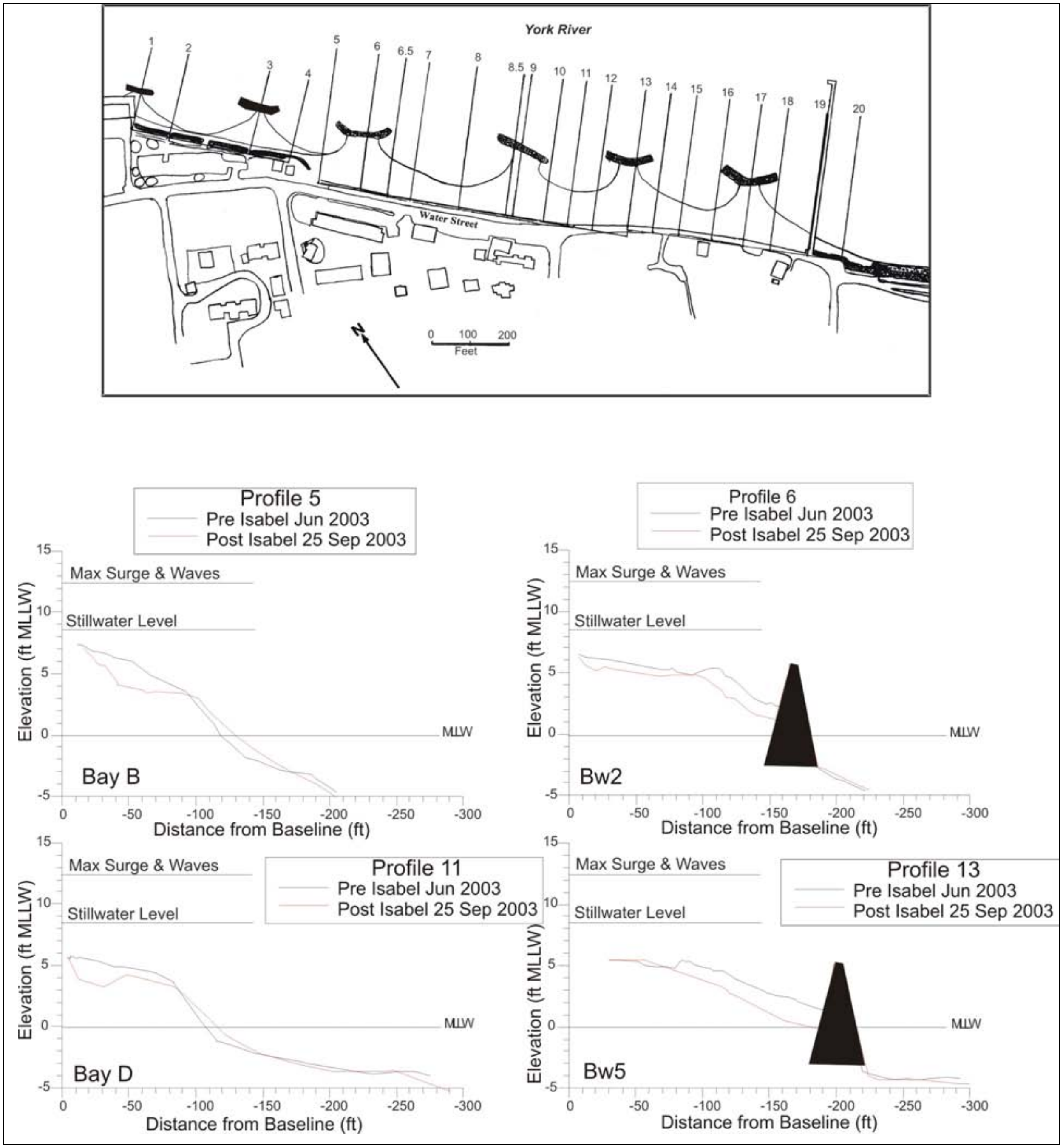


Figure 28. Yorktown baseline and selected pre- and post-storm cross sections

a. View along downriver portion of Water Street

b. View along upriver portion of Water Street at main recreational area

Figure 29. Yorktown ground photographs before and after Hurricane Isabel

a. Pre-storm low backshore

b. Post-storm wrack line

c. Post-storm wrack line downriver

Figure 30. Yorktown

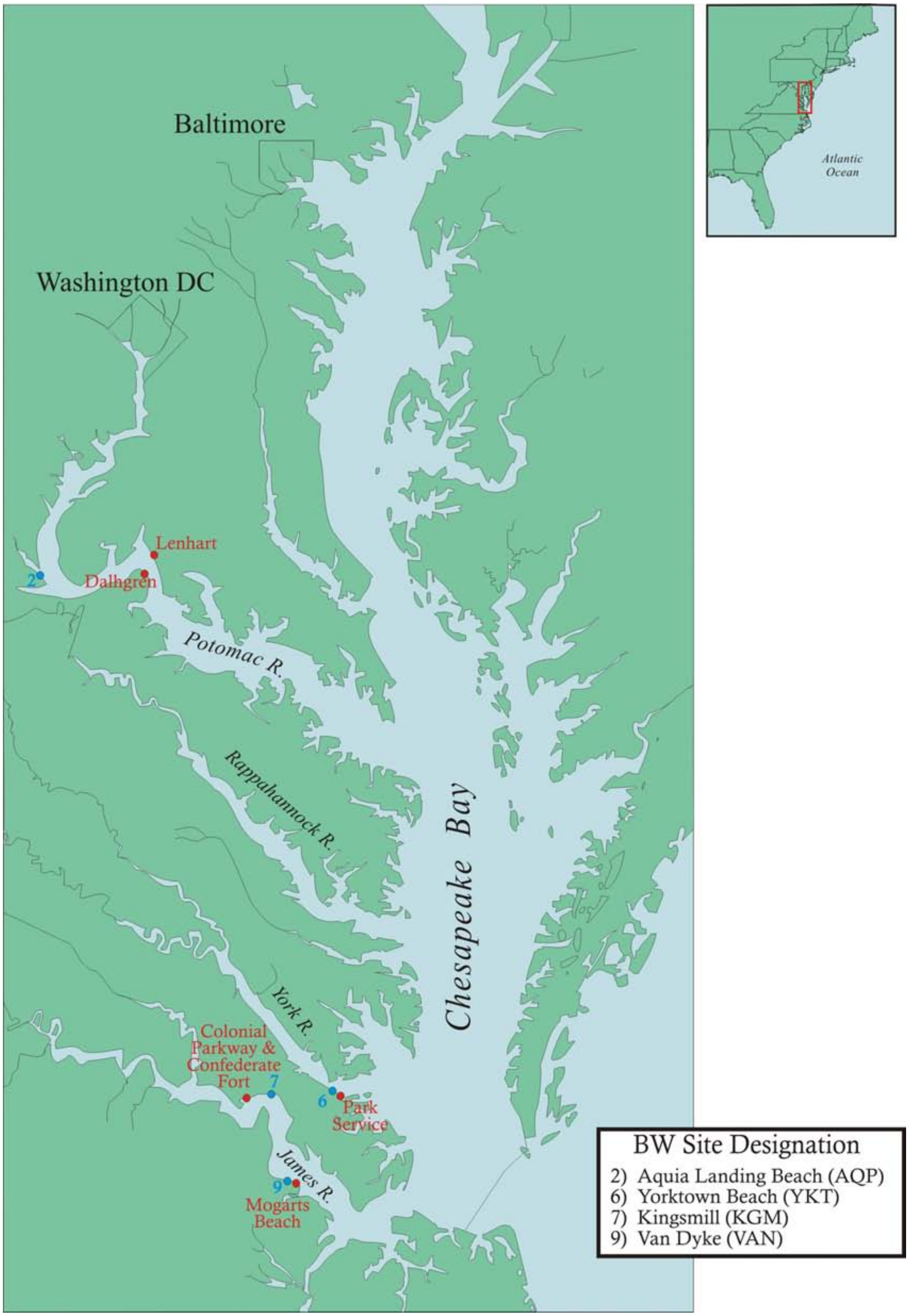
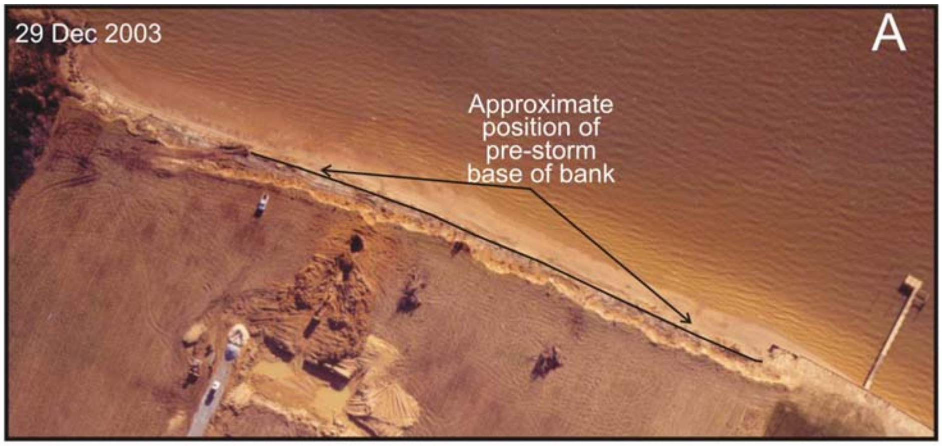


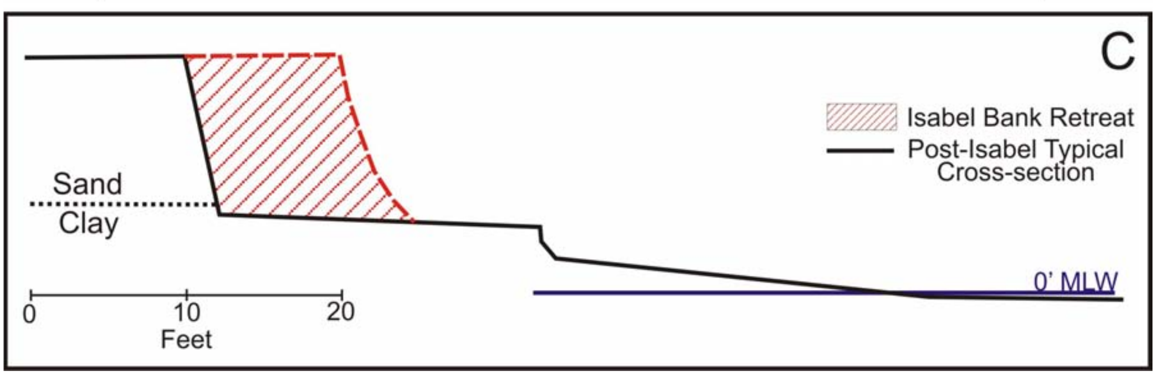
Figure 31. Location of breakwater sites used in this report (blue) and other affected sites (red)

Figure 32. Impacts to unprotected shore at Dahlgren due to Hurricane Isabel



a. Nonrectified aerial photograph

b. Ground photograph



c. Typical post-storm cross section

Figure 33. Impacts to unprotected shore at Lenhart due to Hurricane Isabel

a. At Confederate Fort

b. Along Colonial Parkway

Figure 34. Impact to unprotected shores on James River due to Hurricane Isabel

Figure 35. Impacts at downriver end of Van Dyke where shore is protected by a revetment

Figure 36. Impacts to shore downriver from Van Dyke at Mogarats Beach

Figure 37. Impacts to shoreline downriver from Yorktown Beach at National Park Service's Moore's House

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14. ABSTRACT
The use of breakwaters for shore protection on the Chesapeake Bay has increased over the past 15 years. A multiyear project evaluates post-construction data collected for 41 of these breakwaters and surrounding area including elevation surveys, vegetation, surveys, hydrodynamic analysis and photographs. This information is being accumulated into a database that will be available for evaluation and design reference and to aid in development of design guidance for short-fetch, shallow-water environments of the Chesapeake Bay and similar estuaries. In Fiscal Year 2003, six sites around the bay were chosen for detailed analysis. These surveys were conducted during the months of August and September. Shortly after these surveys were completed, Category 2 Hurricane Isabel hit the area on September 19, 2003. Post-hurricane surveys were immediately conducted at four of the six sites, and the data sets were included in the database. Analysis of these data sets indicates the breakwaters provided significant protection to the land in the lee of the breakwaters and that the structures experienced little or no damage. Additionally, the sand introduced into the sediment budget as a result of the storm cutting into the banks of adjacent unprotected properties may have enhanced the breakwater systems by accelerating the equilibrium beach-building process. This report presents the results of the pre- and post-hurricane breakwater evaluation.

15. SUBJECT TERMS

Chesapeake Bay	Breakwater sites	headland	Section 227
Breakwater systems	Embayments	embayment	
	crest length	cross sections	

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